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BIM FOR BUILDING SUSTAINABILITY ASSESSMENT

Development of a software tool for Rainwater Runoff mitigation

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You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete.

Buckminster Fuller

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ABSTRACT

By the end of the millennium, sustainability had become one of the World's most discussed but arguably least understood topics. With the increasing awareness surrounding this topic, "sustainability" has been applied to most economic sectors. The building industry in particular has a considerable impact on the sustainable actions of our society, considering the immense amounts of resources consumed and the long lasting impact that most of its projects have on our environment (Ebert, Essig, and Hauser 2011). "These facts have prompted the creation of green building standards, certifications, and rating systems aimed at mitigating the impact of buildings on the natural environment through sustainable design" (Vierra 2014). However, although efforts have been made to clearly quantify a sustainable building, the complexity of this term and its outdated assessment, challenge the development of an easy and global evaluation of building sustainability.

In this thesis, using Leadership in Energy and Environmental Design (LEED) as an example for green certifications, these obstacles will be addressed by proposing a method that not only contributes to updating this assessment but also pursues the necessary flexibility to adapt it to different users. However, since sustainability is such a broad topic, this work aims to address a portion of this certification, drawing overall conclusions through the obtained results. This portion is related to stormwater runoff management, focusing on its quantity and quality related problems.

Considering that Building Information Modeling (BIM) is also a rising topic in the Architecture, Engineering and Construction (AEC) Industry, this concept was applied in the development of a BIM-based software to solve the already identified problems. As such, this tool aims to offer a quick, effortless and, most importantly, intuitive way to evaluate the rainfall runoff of a building site, regardless of the building type, while also addressing low-impact development (LID) best managing practices (BMP) to correct it.

In order to introduce these concepts, this thesis starts by exposing the state of the art and theoretical basis concerning these topics. Afterwards, the process of creating the software in Dynamo is thoroughly explained and finally, the designed software is applied to a case study in order to evaluate its performance and better demonstrate its capabilities.

Based on the achieved results, relevant conclusions were retrieved regarding not only the software but also building sustainability assessments and its compatibility with BIM automation features. Through these conclusions it is possible to understand that most credits from these green certifications may easily be subject to automation using BIM, but also allowed for a deeper understanding regarding the necessity of a professional supervising the full process. During this work, conclusions regarding other subjects such as sustainable societies, visual programming languages (VPL) and the application end user were also drawn. Finally, this thesis contributed to the further study and develop of topics like BIM, Sustainability and Automation, even producing optimistic results that justify the continuation of its development in future works.

KEYWORDS: Sustainability, LEED, BIM Automation, VPL, Rainwater Runoff.

RESUMO

No final do milénio, a sustentabilidade tornou-se num dos temas mais discutido no Mundo mas, discutivelmente, um dos menos compreendidos. Com a crescente consciencialização em torno deste tópico, o conceito de "sustentabilidade" começou a ser aplicado à maioria dos sectores económicos, com a indústria da construção em particular a ter um impacto considerável nas acções sustentáveis da nossa sociedade. Facto expectável quando são consideradas as enormes quantidades de recursos consumidos e o impacto de longa duração que a maioria dos produtos desta indústria tem sobre o meio ambiente (Ebert, Essig, and Hauser 2011). "Estes factos levaram à criação de normas de construção, certificações e sistemas de avaliação destinados a mitigar o impacto dos edifícios no ambiente natural através do *design* sustentável" (Vierra 2014). No entanto, embora tenham sido realizados vários esforços para claramente quantificar a sustentabilidade de um edifício, a complexidade deste termo e o seu método de avaliação retrógrado, desafiam uma fácil e global avaliação da sustentabilidade na construção.

Utilizando como exemplo a certificação de sustentabilidade *Leadership in Energy and Environmental Design* (LEED), os obstáculos previamente enunciados serão abordados, propondo um método que não só contribua para a actualização desta avaliação mas também procure alcançar a necessária flexibilidade para adaptá-lo a diferentes usuários. No entanto, uma vez que a sustentabilidade é um tema muito amplo, este trabalho pretende abordar apenas uma parte destas certificações, retirando conclusões dos resultados obtidos que possam ser adaptadas à certificação no geral. Esta fracção a estudar está relacionada com a gestão do escoamento superficial de águas pluviais, com foco nos problemas relacionados com a sua quantidade e qualidade.

Tendo em conta que o *Building Information Modeling* (BIM) é também, actualmente, uma temática bastante debatida na Indústria da Construção, foi realizada uma tentativa de aplicar as noções associadas a este conceito no desenvolvimento de um *software*, com o objectivo de dar resposta aos problemas anteriormente identificados. Deste modo, esta ferramenta tem o propósito de oferecer uma rápida, fácil e, acima de tudo, intuitiva forma de avaliar o escoamento superficial criado na área do edifício, independentemente do seu tipo, ao mesmo tempo que oferece soluções para o diminuir.

A fim de introduzir estes conceitos, esta tese começa por expor o estado da arte e as bases teóricas necessárias à compreensão destes tópicos. Em seguida, o processo de criação do *software* com o recurso ao Dynamo é minuciosamente explicado, seguindo-se a sua aplicação a um caso de estudo, com o intuito de avaliar o seu desempenho e melhor demonstrar as suas capacidades.

Com base nos resultados obtidos, foram retiradas conclusões relevantes não só em relação ao *software*, mas também no que diz respeito à metodologia de avaliação da sustentabilidade em edifícios e à sua compatibilização com ferramentas de automatização BIM. Através destas conclusões, é possível compreender que a maioria dos créditos destas certificações facilmente podem ser sujeitos a uma correcta automatização, contudo, permitiu também verificar a necessidade de existirem profissionais dedicados a supervisionar o processo completo. Durante este trabalho, foi ainda possível retirar conclusões sobre outros assuntos, nomeadamente no que diz respeito às sociedades sustentáveis, às linguagens de programação visual e ao usuário final desta aplicação. Finalmente, esta tese contribuiu para o estudo e desenvolvimento de temas como BIM, Sustentabilidade e Automatização, produzindo resultados que justificam o prolongamento do seu desenvolvimento em trabalhos futuros.

PALAVRAS-CHAVE: Sustentabilidade, LEED, Automatização BIM, VPL, Escoamento Superficial.

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Symbols and Acronyms

Cd – Cadmium

Cu – Copper

Pb – Lead

Zn – Zinc

2D – Two Dimensional

3D – Three Dimensional

4D – Four Dimensional

5D – Five Dimensional

6D – Six Dimensional

7D – Seven Dimensional

AEC – Architecture, Engineering and Construction

ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers

API – Application Programming Interface

BIM – Building Information Modeling

BMP – Best Managing Practices

BREEAM – Building Research Establishment Environmental Assessment Method

CAD – Computer Aided Design

CFC – Chlorofluorocarbons

CSR – Corporate Social Responsibility

DDT – Dichlorodiphenyltrichloroethane

FEUP – Faculdade de Engenharia da Universidade do Porto

FM – Facility Management

GSA – General Services Administration

GUI – Graphical User Interface

HP – Hewlett-Packard

IDF – Intensity-Duration-Frequency

LEED – Leadership in Energy and Environmental

LID – Low-Impact Development

LOD – Level of Development

PCB – Polychlorinated Biphenyl

PTC – Parametric Technology Corporation

SBTool – Sustainable Building Tool

SDK – Software Development Toolkit

THP – The Hannover Principles

TLS – Three-Legged Stool

TNS – The Natural Step

TOC – Three Overlapping Circles

TPS – Three Pillars of Sustainability

UNFCC – United Nations Framework Convention on Climate Change

USGBC – United States Green Building Council

VPL – Visual Programming Language

WCED – World Commission on Environment and Development

1
INTRODUCTION

This work falls within the scope of the curricular unit *Dissertação em Construções* from the Master in Civil Engineering course at *Faculdade de Engenharia da Universidade do Porto* (FEUP).

This initial chapter has the intention to conduct a brief introduction to the studied subject, starting with its framework (1.1), followed by the motivation (1.2), the addressed objectives (1.3) and finally the dissertation structure (1.4).

1.1. FRAMEWORK

In recent decades the computing capabilities to represent and analyze three-dimensional models for buildings has increased significantly. More recently, the appearance of **Building Information Modeling** (BIM) shifted the Architecture, Engineering, and Construction (AEC) Industry from a drawing-based, Computer Aided Design (CAD) sector to a generation, management and transfer of information-centered industry.

The growing demand for efficient buildings fomented the AEC industry to exploit the potential offered by these technological advances. Aspects such as simulation and performance analysis, mathematical optimization and even process automation have begun to innovate the construction industry, arousing attention to a new way of modeling test buildings inside a virtual environment. Nowadays, the industry instigates the understanding behind a digital model, perceiving three-dimensional modeling not only as a representation, but also as a virtual prototype to test real conditions and retrieve indispensable information to achieve the necessary efficiency required by stakeholders. The more improved and efficient these simulations are along the initial stages of design, the greater the potential for overall success for the project.

To further achieve this purpose and reach better simulation results, parametric modeling has proven to be a very effective tool. Parametric modeling enables the creation of flexible and adaptable models that can be combined with analysis, optimization and automation tools. This way, it increases the overall efficiency of the building design. Moreover, currently these tools are able to integrate a BIM environment, allowing for an even better usage. Although the dissemination of these tools is still not significant, it is also true that more and more stakeholders have realized the potential of exploiting them and that regulations have been established in different countries, determining mandatory BIM delivery in certain projects.

In this context, the parametric modeling tools based on 3D CAD software, like Revit and Rhino, extend these qualities by offering interfaces for visual programming (such as Dynamo and Grasshopper), which allow the generation of parametric models. In addition, these tools allow a wide customization through a set of plug-ins that extends its native capabilities. These plug-ins, mostly developed by third parties, allow the incorporation of performance simulations with multiple interoperability systems (including BIM), solve problems using optimization techniques, and are able to significantly automate procedures. This not only imbues these tools with great flexibility but also the necessary adaptability to be applied on the vast majority of projects from the AEC.

The creation of parametrically defined models enables the incorporation of generative processes modeling, also known as generative design. This process allows the replacement of the idea of a static model, typical of CAD and non-parametric BIM models for dynamic ones. That is, models that respond with geometric changes to criteria functions defined by the designer, creating and evaluating multiple design alternatives. Thus, the generative processes allow the designers to further apply their expertise through the use of parametric code. This process flexibility enables the designers to foster new ideas and unleash their creativity as the author.

The use of simulation and computational analysis tools, together with optimization techniques, allows for multiple performance criteria to be simultaneously analyzed. Thus, it is possible to obtain a spectrum of solutions that meet the pre-defined indicated objectives. With this data, the design team can then evaluate and compare various solutions and choose the best overall fit for the project objectives. With this in mind, in this thesis these new technological capabilities will be exploited within the topic of **sustainability in construction**.

By the end of the millennium, sustainability had become one of the World's most discussed but arguably least understood topics. With the increasingly awareness surrounding this gradually important topic, this concept has been applied to most economic sectors, with the building industry in particular having a significant impact on the sustainable actions of our society, considering the immense amounts of resources consumed and the long lasting impact that most of its projects have on our environment (Ebert, Essig, and Hauser 2011, Junnila and Horvath 2003). "These facts have prompted the creation of green building standards, certifications, and rating systems aimed at mitigating the impact of buildings on the natural environment through sustainable design" (Vierra 2014). These environmental assessment methods for buildings were the first step towards greener and more sustainable buildings. By evaluating their sustainability performance, buildings are placed inside a determined rating system that then attracts economic and social advantages for the owner while socially and environmentally helping the community surrounding it.

These tools, which first appeared in the 1990s, had an exponential growth in the early 2000s as seen by the 17 tools reviewed by Haapio and Viitaemi (Haapio and Viitaniemi 2008), only five of which are among the 26 revised by Khasreen et al. (Khasreen, Banfill, and Menzies 2009). This fact is commonly attributed to the scoring of these certificates being heavily influenced by the type of building being studied (Saraiva, Almeida, and Bragança 2015) and the "countries climatic, cultural and legal situations" (Ebert, Essig, and Hauser 2011). As such, despite their evaluated concepts and needs, such as water efficiency, energy consumption, material use, building location and indoor environmental quality (Azhar *et al.* 2011), being fairly similar, this means that currently there are tens of certificate systems operative in different countries resulting in hundreds of these tools around the world.

Most of these tools are based upon BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design) and SBTool (Sustainable Building Tool). In this thesis, LEED was the chosen certificate to represent these tools, thus being deeper explored across this work.

LEED is a voluntary, consensus-based, rating system established by the United States Green Building Council (USGBC) to assess the environmental sustainability of buildings designs. (USGBC 2005) After its introduction in 2000, the market diffusion and popularity of LEED green building certification has been gradually increasing all over the world, fact most noticeable in the recent years (Scofield 2013). Throughout their 16-year history, LEED has remained one of the most, if not the most, accepted benchmark for designating “green buildings” around the world (Cidell 2009). As most green rating systems, LEED presents itself has a straightforward checklist. This checklist is comprised of credits related to the topics previously mentioned, one of which is the **rainfall runoff**.

The percentage of urban population worldwide is steadily increasing (Programme 2008). As such, urban areas are continuously expanding in terms of space and density. One side effect of this urbanization is the increase of impermeable surfaces. This in turn has numerous consequences for the city infrastructure and neighboring environment (Berndtsson 2010).

The impact the rainfall runoff has on ecosystems is exacerbated by this urbanization. Since infiltration decreases, the stress on existing stormwater infrastructure rises. This in turn creates severe problems in a large number of urban areas, such as water pollution, flooding, groundwater recharge deficits, and ecological damage to urban streams (Thurston 2006). Proliferation of impervious surfaces allows rainfall water to reach streams faster which causes higher peak flows that can create stream alterations, habitat degradation and floods. Since impervious surfaces stop water from infiltrating the soil, less water is available for groundwater recharge, which reduces stream base flow. Also, depending on the land use inside the watershed, nutrients, toxins, and suspended materials, among others, can be obtained from roadways, parking lots, and other infrastructures. These pollutants will be transported overland into waterways causing toxic loading on the stream. This way, rainfall runoff can not only be a main pollution problem but also a potential pollution source. (Arnold Jr and Gibbons 1996) However, if these pollutants are effectively removed this water can be turned into a potentially beneficial resource. With this intent, Low-Impact Development (LID) Best Managing Practices (BMP) should be implemented.

Conventional storm water infrastructure, which is still predominant in urbanized areas, is intended to quickly convey water from the city to natural recipients. When the idea of sustainable development acquired more ground in the early 1990s, the urban water infrastructure was target to major rethinking. As such, nowadays stormwater is recognized as an important resource to be used for social benefit and from which advantages are frequently more extracted. As such, LID–BMP normally intends to store rainfall through long periods of time, reusing it, infiltrating it, or simply evaporating it, after which, the remaining rainfall is slowly released into the stream. With this purpose LID–BMP implementation should be entirely coordinated with the local construction plan and integrated, if possible, into the site landscaping scheme. In order to achieve this goal these measures need to be designed into the earliest phases of the project (Jia *et al.* 2012).

Finally, although efforts have been made to clearly quantify a sustainable building, the complexity of this term and its outdated and ambiguous assessment challenge the development of an easy and global evaluation for building sustainability. In fact, the time and cost required to acquire these certificates can be so great that owners reconsider the advantages of obtaining these green seals.

Thus, this thesis explores the concepts outlined above with the intent to answer these problems by the means of an automated software. It is expected that both Sustainability and BIM captivate even more professionals to its research and use, integrating these topics in the AEC Industry in order to extract their advantages as two separate concepts or together as in this thesis.

1.2. MOTIVATION

Building sustainability has been object to extensive discussion in the last few years, mainly because of the increasing awareness surrounding this topic. However, when comparing the recognized urgency attributed to this topic with what actually has been done towards achieving building sustainability, it is possible to conclude that not many efforts have been directed towards this goal. As such, with the author's intent to contribute to this achievement, this thesis hopes to create an evaluation method to, at some extent, facilitate the assessment of a building's sustainability.

Similarly, BIM is another topic that has been growing in importance in the AEC Industry. In the last few years, more predominantly in the last few months, BIM has even approached sustainability, connecting both of these topics with the purpose of using BIM capabilities to achieve building sustainability. Thus, it is the author's resolve to also contribute to this recent connection, fortifying it, and demonstrating that BIM capabilities can and should be used on the pursuit for building sustainability.

It is through this lens that the current thesis emerges. Although these concepts have been learned and discussed in the last few years through the syllabus of the Civil Engineering Department at FEUP, the author's interest for these broad topics created the intent to deeper research these concepts, extending his knowledge of Sustainability and BIM, while also achieving a thesis that contributes to linking them both. In the author's opinion it is up to us, Civil Engineers, to find methods to better achieve building sustainability, creating a better image for our industry while helping to preserve the world.

1.3. OBJECTIVES

Facing the previous framework and motivation, it was considered fundamental to previously engage studies regarding Sustainability and BIM. It was also decided to explore recently developed software related to these topics, with the intent to create an original program. As such, the following objectives contribute to this purpose:

The first main objective of this thesis is to highlight the importance of sustainability not only to the construction sector but also to society itself. In this sense, it will be possible to unravel the consequences of the ill definition of sustainability, understand the rise of public awareness, and perceive the creation and implementation of frameworks and tools with the purpose of achieving a more sustainable society. These tools will be mostly connected to the AEC Industry, reviewing topics such as green building and sustainability certifications, focusing primarily in LEED and its credits related to rainwater runoff.

The complexity intrinsic to such a broad concept as sustainability is hard to address without prolonging its study, however in this work a more objective approach is followed, addressing certain aspects of sustainability in a more conservative way, circumventing some of the most complex and discussed topics when appropriate and relying upon facts to deliver concise conclusions regarding sustainability.

A second objective is the study and exploration of the more recently divulgated concept of BIM. This topic has been rising within our industry and will, certainly, keep evolving not only in importance but also in complexity. As such, it is an aim of this work to understand the full length and impact of this concept, exploring Revit as the main connection to BIM and, in order to achieve its full potential, Dynamo – Revit's visual programming language (VPL).

Following this last topic, the third objective holds the creation of a sustainability focused software linked to the AEC Industry. This tool is intended to automatically determine the rainfall runoff of any building site, regardless of the building type, followed by the proposal of means to actually correct it. This way, it is sought to retrieve the maximum potential from Dynamo, while uncovering its advantages, disadvantages and practical qualities alongside Revit.

Finally, with the intent to better understand the designed software capabilities and restrictions, it will be applied to an existing building.

In short, the objectives can be summarized in the following four topics:

- Approach the topic of sustainability with the objective of understanding its importance, its connection to the AEC Industry, and what has been done to achieve a sustainable society;
- Approach the topic of BIM, exploring its recent evolution in importance, Revit and Dynamo, in order to efficiently create a software capable of connecting both these topics;
- Design and create a software linked to the two previously mentioned concepts;
- Test the created software, applying it to an existing building.

With the objectives aforementioned, this thesis seeks to propel the knowledge regarding sustainability, BIM, and their possible cooperation, proposing a new software to aid in this union in a simple, practical and efficient way.

Finally, this thesis, had to be developed along 4 months, between March and June of 2016, as such, the initial goals had to be narrowed in order to produce a final document with the desired quality, practical relevance and strong conclusions. This way, some initial objectives, not mentioned in this section, had to be shifted to future works and will be exposed in the conclusion chapter.

1.4. STRUCTURE

The present work was divided in 6 different chapters which encompass the following content:

- Chapter 1 – Introductory in nature, this chapter establishes the framework and motivation for this thesis, define its objectives and present its structure;
- Chapter 2 – Corresponds to the literature review on the topic of *Sustainability in Construction*. The chapter describes the concept of sustainability, what it really means to be a sustainable society and the impact the Architecture, Engineering, and Construction Industry has on achieving this goal. While overviewing the main tools and efforts towards this objective, a special emphasis is given to Green Certification Systems and its relation with the rainfall runoff;
- Chapter 3 – Much like the previous chapter, Chapter 3 corresponds to the bibliographic study on *Building Information Modeling*. Its main objective is to address BIM, its dimensions, their respective evolution, and establish a link between the proposed software and the necessary tools used to create it;
- Chapter 4 – Chapter 4 presents the software that has been developed to calculate the rainfall runoff. The chapter helps understand the evolution of the designed software, since the conception of the general workflow for the program, to the construction of the necessary databases and writing of raw code in Dynamo. This way, it will be possible to realize what is behind the Revit interface seen in the final product;
- Chapter 5 – This chapter consists on a case study comprising the application of the created software to part of the G building of FEUP. As such, a brief description of the building is given as well as a full analysis of the results offered by the program. All the necessary modifications done to the Revit model are also shortly demonstrated;
- Chapter 6 – In this final chapter, the main conclusions achieved across this work are presented with the intent to answer the initial proposed objectives. The major difficulties found along this thesis are described and a brief reference to possible future work is made.

2
SUSTAINABILITY IN CONSTRUCTION

2.1. THE PROBLEMS OF DEFINING SUSTAINABILITY

"Sustainability, the World's most present concern" is arguably a prevalent view on this topic. In the last few years "sustainability" has become a fashionable word not only among researches but also among the general public (Gatto 1995) and, by the end of the Millennium, this term became a guiding principle for the future prosperity of the human population (Keiner 2005). The quick spread of scientific data regarding this topic and all the advertisement linking the Global Warming and other world crises to the sustainability problem (i.e. Davis Guggenheim documentary film *An Inconvenient Truth*, 2006, featuring the former American Vice President Albert Arnold "Al" Gore, Jr.) have raised concerns on this matter. This resulted in an increasing apprehension over long sustainable debates, such as, the exploitation of natural resources, and the economic development at the expense of environmental quality (Keiner 2005). Although the accuracy of this information has yet to meet a consensus (Ludwig 1993), it is clear to the larger scientific community that "sustainability" is one of the, if not the most, priority concern the nation's leaders have to answer (Gatto 1995). However, while "sustainability" is widely invoked to validate "actions or lack of actions", the scientific community is yet to reach an agreement on the exact meaning of this term (Kidd 1992). In this section, it will be possible to understand the definition of sustainability, allowing for a better understanding of how this problem came to be and what has been done to prevent it from escalating.

Being a broad and complex concept, sustainability has more than two hundred different definitions, all of which are correct in its own way. If fact, the roots of this term are so deeply embedded in such a variety of different concepts, that the pursuit for a single definition is not only challenging but also almost futile (McKeown and Nolet 2012, Kidd 1992). However, as it will be possible to conclude, this is only aggravated by the fact that the most common definition for sustainability does not actually define sustainability.

In its origin, "sustainability" is derived from the Latin *sustinere*, which can be traced to the word *tenere*, "to hold", "to maintain", "to endure". Although this is not the actual definition, it helps to understand its meaning and how the first idea of sustainability appeared. In 1713, the first book on forest sciences is edited by Carlowitz. In it, the author argues that since timber was rising in importance, it should be monetarized with caution, maintaining "the balance between timber growth and lumbering". This would in turn make a possible sustainable future for this natural resource. He writes: "For this reason, we should organize our economy in a way that we won't suffer scarcity [of timber], and where it is lumbered we should strive for young growth at its place" (Von Carlowitz and von Rohr 1732). This base idea was later redefined as a broad political vision in 1987, at the World Commission on Environment and Development (WCED), originating the popular definition on "sustainability" (Keiner 2005). Yet, since this redefinition was essentially ill made, the resulting consequences of a flawed concept as vast as sustainability were massive. Nonetheless, the flaw was simple, the new definition of "sustainability", presented at WCED, did not actually define "sustainability": "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). This definition can also be seen in Figure 2.1. As it can be easily perceived, this definition clearly defines "sustainable development" and not "sustainability". As such, what was failed to understand was that "sustainable development" is the solution and not the problem to be solved. Still, this was the definition most commonly used for sustainability.

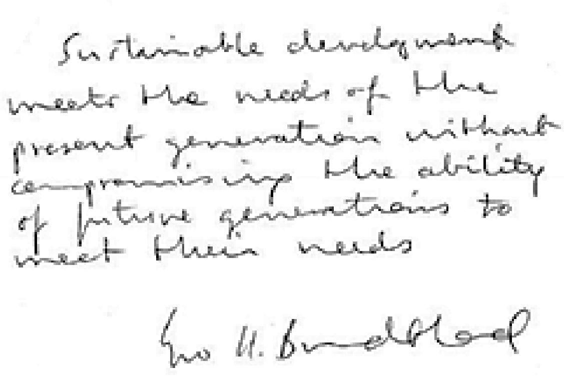

Fig. 2.1 – The definition of Sustainable Development (autograph of Gro Harlem Brundtland). Source: adapted from (Keiner 2005)

From analyzing this definition it is clearly perceivable that we, as humans, have a moral responsibility to consider not only the welfare of the present population but also the welfare of the future generations and so, by extension, the effects our actions and activities will have on their lifestyle (Kibert *et al.* 2011). But what "needs" should be addressed?

United Nations Stockholm Conference on the Human Environment, 1972. The first known world conference to focus on this matter which debated the "need for a common outlook and for common principles to inspire and guide the peoples of the world in the preservation and enhancement of the human environment" (Sohn 1973). Maurice Strong was the secretary general for the conference. In his book *Where on Earth Are We Going*, 2000, he writes: "the biggest threat to the conference was the ambivalence, even antipathy, that developing countries felt toward the whole issue of development" (Strong 2010). In fact, to these countries in order to achieve a sustainable development, concerns such as pollution and environmental contamination were not to be addressed at such an "initial stage". Such problems were part of being a "rich" country, and so, only they should address environmental sustainability, allowing developing countries to solve problems such as underdevelopment and poverty. And although common goals where outline in this conference, it was clear that "most of them would exchange a little pollution for the benefits of economic growth" (Strong 2010).

This was a dramatic problem. However, revising once again the definition of "sustainable development" it is impossible to conclude they were wrong. After all, to a developing country, poverty and underdevelopment are in fact a "need" to be answered. Thus, it is now clear that this definition would be a failure. But how could we correct this definition? What is really "sustainability"?

The answer to this last question was subject to several modifications and was re-formulated according to many different points of views. Despite today, more than ever, disagreement persisting on the exact meaning of this term, the most known answer, and therefore the commonly accepted definition for "sustainability", was offered by the Enquete Commission of German Bundestag on *The Protection of Humanity and the Environment*, 1994. Here we can find that "sustainability is the concept of a lasting forward-looking development of all economic, ecological and social aspects of human existence. These three pillars of sustainability are interdependent and require a balanced coordination" (Enquete Comission 1994). As such, it is possible to determine that a sustainable society results from the fragile balance between the economic, social and environmental aspects, also known as the "Three Pillars of Sustainability" (TPS), seen in Figure 2.2. Each of these pillars obviously represents one three aspects:

- The Social Pillar of Sustainability:

Social sustainability is the ability of a given social system, for instance a country, organization, community or even a family, to achieve a certain level of social well-being and harmony indefinitely (Circular Ecology 2015). Issues such as endemic poverty, low education rates, widespread injustice, and war, are symptoms of an unsustainable social system.

- The Environmental Pillar of Sustainability:

Environmental sustainability is the ability of our surrounding environment to support a certain level of environmental quality, while capable of sustaining a defined rate of resource extraction indefinitely (Daly 1990). Currently, this is, as already stated, one of the World's most present concern, embodying issues such as mineral resource depletion, overfishing, loss of biodiversity, desertification, among other problems (Kibert *et al.* 2011). This pillar supports initiatives such as recycling, renewable energy, good waste management, reducing fossil consumption and emissions, organic farming, tree planting and reducing deforestation.

- The Economic Pillar of Sustainability:

Economic sustainability is the ability to support a certain level of economic production indefinitely (Circular Ecology 2015). This requires that an economic cell, such as a business or a country, applies its resources efficiently and responsibly, originating a consistently operational profit. In the last few years, especially after the Great Recession of 2008, the world economy and its related concerns became a frequent mediatic topic, endangering and disrupting the necessary balance between these three pillars.

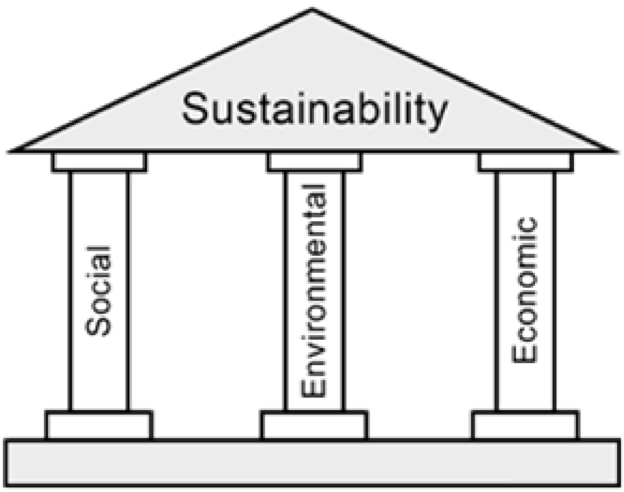

Fig. 2.2 – The Three Pillars of Sustainability. Source: adapted from (Jones 2013)

Accepted the Enquete Commission of German Bundestag definition of sustainability, it is now possible to determine the consequences of a non-sustainable society. This topic will be addressed in the following section alongside the identification of what has been done to improve this topic and which frameworks were created to achieve a sustainable outcome for society.

2.2. CONSEQUENCES OF A NON-SUSTAINABLE SOCIETY AND THE RISE OF GLOBAL CONCERN

Sustainability was always a thing; it has existed since the beginning of times. In fact, as already demonstrated by the TPS, sustainability covers all aspects of life and, despite this, humanity payed close to no attention to this matter simply because it was not a problem. The variations on our planet sustainability were too dim to be detected since our impact on the planet was almost unnoticeable. However, in recent decades, most prominently after the industrial revolution, our lifestyle and demand for more sources of energy and materials changed our mainly agricultural focus industry into and industrial society (Ebert, Essig, and Hauser 2011).

2.2.1. THE CONSEQUENCES

This transformation started around the end of the 18th century in the wealthier countries throughout Europe and North America, and continued through Japan and other parts of Asia in the late 19th century. Along with these changes came an enormous boost for countries' economies and, although it took some time to notice, an enormous negative impact on our planet. In fact, by 2010, the "world's wealthiest countries, with less than 20 percent of the world's population," contributed to over "40 percent of all global carbon emissions, and were responsible for more than 60 percent of the total carbon dioxide that fossil fuel combustion has added to the atmosphere since the Industrial Revolution began" (Kibert *et al.* 2011). Moreover, in recent years, with the development of countries like China, India and Brazil, this impact became more tangible and grew at an even higher rate. By 2007, China's fossil fuel emissions exceeded those of the United States and continued to rapidly grow, rising at 10 percent a year, which is 10 times higher than the average rate for industrialized nations. Also, "global population [continues] to grow at an alarming rate, with a population the size of Mexico (about 80 million) being added to the planet each year" (Kibert *et al.* 2011). In fact, recent demographic studies (Lutz 2013) indicate that by 2030 the World's population, even in the most conservative scenario, will increase by 50 percent, with developing countries representing up to 87 percent of the total (Gatto 1995). As such, ripples originated from these changes could now actually be noticed, not only on the economic and social aspects of society, but also on the environment which, theoretically, humanity could not influence, being the planet such an ancient and much bigger "being" than humans.

As seen in the last paragraph, the first issues to be noticed by this non-sustainable society where the enormous population and economic growth, the poverty surplus and the rapid urbanization. This caused an enormous growth in consumption, shortage of food, increased disease and waste production, intensifying not only the problems already encountered but also provoking new ones (Ebert, Essig, and Hauser 2011). In fact, these social and economic problems where followed by other, more environmental related issues such as climate change, loss of biological diversity, increasing soil degradation, deforestation and extreme soil use, air pollution, shortage of drinking water and even a higher occurrence rate of natural disasters such as floods and droughts, storms and tornados, volcanic eruption and earthquakes (Kibert *et al.* 2011). This last few aspects shown more intensely that this dramatic change on our lifestyle could in fact be destroying the balance of our planet's sustainability, which propelled the scientific community to arrive at a consensus implying human activity as the major contributory factor for these issues. However, although these concerns were reaffirmed by the drastic dependence of non-renewable fossil fuels shown by the 1973 and 1979 energy crises, not much was done to correct it (Ebert, Essig, and Hauser 2011).

Yet, in the end of millennium, dramatic findings made public from a succession of reports such as *Silent Spring* (1962), *The Population Bomb* (1968), *Tragedy of the Commons* (1968), *Blueprint for Survival* (1972), *Limits to Growth* (1972), *Global 2000 Report to the President* (1982), *State of the World* (1984), *Resourceful Earth* (1984), *Our Common Future* (1987) and finally *Earth in Balance* (1992), pushed governments to interfere. (Carson 2002, Annan, Flavin, and Starke 2002, Simon and Kahn 1984, Ehrlich 1970, Meadows *et al.* 1972, Barney 2013, Brundtland 1987, Al Gore 1992, Hardin 1968, Goldsmith and Allen 1972) This in turn propelled a succession of international conferences regarding our World's and society's sustainability in the last decades.

2.2.2. SUSTAINABILITY CONFERENCES

The first of these conferences was suggested by Sweden to the United Nations Economic and Social Council in 1968. After being passed by the General Assembly Resolution 2398 in 1969, it lead to the first United Nations conference on sustainability: the United Nations Stockholm Conference on the Human Environment. Held in 1972, this conference regarding "human interaction with environment and the immerging environmental issues", resulted in a handful of important documents such as the *Declaration on the Human Environment* and the *Action Plan for Human Environment*.

In the following years other minor conferences such as the United Nations World Food Conference, Rome, Italy, 1974; the United Nations World Water Conference, Mar Del Plata, Argentina, 1976; and the United Nations Conference on Desertification, Nairobi, Kenya, 1977, took place. Despite not being as important as Stockholm, the fact that non-governmental organizations such as The Worldwatch Institute, The World Resource Institute, The Indian Science Congress Association, The International Institute for Applied Systems Analysis, and The World Bank kept stimulating debate regarding this conferences, not only popularizing the term "sustainability" but also helped to develop the basis for further action (Kidd 1992, Hardin 2009).

Next, the First World Climate Conference was held in Geneva, Italy, 1979, resulting in the *World Climate Program*. This conference was quickly followed by the United Nations Vienna Conference, in Vienna, Italy, and the Villach Conference, in Villach, Austria, both in 1985. These conferences focused on assessing the ozone layer problems, and resulted on the *United Nations Vienna Convention on the Protection of the Ozone Layer* and in the *Montreal Protocol on Substances that Deplete the Ozone Layer*, two years later.

Afterwards, the International Conference of the Changing Atmosphere was held in Toronto, 1988. This conference elevated the sustainability problems, such as the Global Warming, to a new level, being internationally recognized as "second only to nuclear war" (Ferguson 1988). As such, an alarming schedule for change was created, employing laws and goals into effect, and spawning a rapid succession of conferences. The most impactful of such conferences are (UNFCCC 2014):

- The Second World Climate Conference, Geneva, Italy, 1990;
- The United Nations Conference on Environment and Development, also known as Earth Summit, Rio de Janeiro, Brazil, 1992. Which produced the *United Nations Framework Convention on Climate Change* (UNFCC) implementing a yearly conference on Climate Change – the Conferences of the Parties;
- The International Conference on Population and Development, Cairo, Egypt, 1994;

- The First Conference of the Parties to the UNFCCC, Berlin, Germany, 1995;
- The Earth Summit +5, New York, United States of America, 1997;
- The Third Conference of the Parties to the UNFCCC, Kyoto, Japan, 1997, in which the *Kyoto Protocol* was finished;
- The Lisbon European Summit, Lisbon, Portugal, 2000, where the Lisbon Strategy for the period of 2000-2010 was created and which would influence the Europe 2020 strategy;
- The World Summit on Sustainable Development, Johannesburg, South Africa, 2002;
- The Third World Climate Conference, Geneva, Italy, 2009;
- And finally, The United Nations Conference on Sustainable Development, Rio de Janeiro, Brazil, 2012.

As seen by the amount of conferences enumerated (which only translate into a small portion of all the sustainability conferences), along the last few years much has been done to achieve a sustainable society. International agreements, sustainable certifications, and awareness strategies, such as the “Three R Policy”, the “Save Water Policy”, the “Majestic Plastic Bag” campaign, and the “Don’t Waste Paper” campaign, are some examples of these efforts. In the following section a short overview of the most influential frameworks created by the scientific, economic and scholar communities in which most of these actions are based upon is presented, to offer a better understanding of these strategies foundations.

2.3. FRAMEWORKS FOR A SUSTAINABLE SOCIETY

As described by Sharachchandra Lélé the examination of this topic, “sustainability”, goes from the most trivial and contradictory interpretations to the most meaningful ones. “Since sustainability emphasizes the constraints and opportunities that nature presents to human activities, ecologists and physical scientists frequently dominate its discussion. [This creates a great focus on] the ecological conditions for ecological sustainability -- the biophysical "laws" or patterns that determine environmental responses to human activities and humans' ability to use the environment” (Lele 1991). However, as already stated in this thesis, in conjugation with these ecological conditions, there should also exist economic and social conditions that influence not only the people-environment interactions and thus the ecological sustainability but also the economic and social interactions which are clearly needed to define a sustainable society.

In this section the most established frameworks that rely on these three corner stones to achieve a sustainable society will be reviewed: The Hannover Principles, The Three-Legged Stool and its variations, The Natural Step, and Corporate Social Responsibility. This will not only help to further understand the concept of sustainability but also create a solid base to support the development of the next sections, in which the measures created to achieve a sustainable society will be addressed.

However, it is important to refer that in this chapter it will only be possible to overview some of the basic principles and contradictions behind these frameworks, not referring to the most complex and advanced discussed topics about this sustainability models.

2.3.1. THE HANNOVER PRINCIPLES

In 2000, the city of Hannover, Germany, was the site for the World Fair. Being the theme for EXPO 2000 “Humanity, Nature, and Technology”, the city decided to address the issues relating to sustainability. In order for the site to represent a sustainable development for the city, region, and even the world, the City of Hannover commissioned “The Hannover Principles” (THP). These principles developed by William McDonough and Michael Braungart, were to be considered by all entities involved in establishing the site for the World Fair, as well in setting priorities for the built environment. THP would help form “the foundations of a new design philosophy underlying the future of proposed systems and construction for the City, its region, its global neighbors and partners in the world exposition.” “The Hannover Principles should be seen as a living document committed to the transformation and growth in the understanding of our interdependence with nature, so that they may adapt as our knowledge of the world evolves” (Braungart and McDonough 1992). These principles are as follows:

Table 2.1 – The Hannover Principles

1. **Insist on rights of humanity and nature to co-exist** in a healthy, supportive, diverse and sustainable condition.
2**. Recognize interdependence**. The elements of human design interact with and depend upon the natural world, with broad and diverse implications at every scale. Expand design considerations to recognizing even distant effects.
3. **Respect relationships between spirit and matter**. Consider all aspects of human settlement including community, dwelling, industry and trade in terms of existing and evolving connections between spiritual and material consciousness.
4. **Accept responsibility for the consequences of design** decisions upon human well-being, the viability of natural systems and their right to co-exist.
5. **Create safe objects of long-term value**. Do not burden future generations with requirements for maintenance or vigilant administration of potential danger due to the careless creation of products, processes or standards.
6. **Eliminate the concept of waste**. Evaluate and optimize the full life-cycle of products and processes, to approach the state of natural systems, in which there is no waste.
7. **Rely on natural energy flows**. Human designs should, like the living world, derive their creative forces from perpetual solar income. Incorporate this energy efficiently and safety for responsible use.
8. **Understand the limitations of design**. No human creation lasts forever and design does not solve all problems. Those who create and plan should practice humility in the face of nature. Treat nature as a model and mentor, not as an inconvenience to be evaded or controlled.
9. **Seek constant improvement by the sharing of knowledge**. Encourage direct and open communication between colleagues, patrons, manufacturers and users to link long term sustainable considerations with ethical responsibility, and re-establish the integral relationship between natural processes and human activity.

Through THP the definition of sustainability can be extended, approaching the importance of design which must fulfill “the needs and aspirations of the present without compromising the ability of the planet to sustain an equally supportive future” (Braungart and McDonough 1992). This new approach molded this two concepts creating “sustainable design” with the purpose to “eliminate negative environmental impact completely though skillful, sensitive design”. (McLennan 2004)

However, although nowadays this concept is embedded in architecture, urban planning, and most areas of design, most times it hasn’t been correctly applied. In his book *Design is the problem: the future of* *design must be sustainable*, Nathan Shedroff explains that “design has sometimes created big problems in the world. Even where our best intentions have been engaged, our outcomes have often fallen short.” At the International Council of Societies of Industrial Design he also states that “design is a big part of the sustainability problems in the world. Design has been focused on creating meaningless (often), disposable (though not responsibly so), trend-laden fashion items – all design” (Shedroff 2009).

2.3.2. The Three-Legged Stool and its variations

The Three-Legged Stool (TLS) is, by far, the framework that better retains the basic principles from the TPS concept and is also the most commonly applied. This metaphor illustrates the necessity for the balance (“length”) of the environmental, economic and social aspects of society to be maintained, otherwise the stool with collapse. On the downside the same metaphor transmits the idea that all the three “legs” are separated, which is far from the truth (Willard 2010).

Fig. 2.3 – The Three-Legged Stool. Source: adapted from (Gerber 2010)

In response to this problem and according to the World Conservation Union the TLS can be portrait with its three dimensions being drawn either as Embedded Circles or in the popular Venn diagram of Three Overlapping Circles (TOC) (Adams 2006). These are the diagrammatic representations of sustainability and represent the two variations of the TLS model.

The TOC model “stresses the importance of the interactions between the three areas” and “emphasizes the need for an interdisciplinary and transdisciplinary approach to understanding sustainability” (Todorov and Marinova 2009). However, although TOC “has proved to be a very popular and palatable way of relating the conceptual complexity of sustainability to a wide audience”, “evidence exists of the Venn diagram representation being adapted to suit the requirements of specific interests” (Moir and Carter 2012). In fact, one particular aspect related to the Venn diagram is the possibility to re-size the different circles according to our priorities as shown in Figure 2.4. As such, despite the international efforts led by the United Nations to frequently portrait all the three circles being the same size, this is not what actually happens. Although still maintaining the important interactions between the different dimensions this detail demolishes the supposed necessary equality between them. As such, in Figure 2.4 it is possible to understand how disparate the results are between the “theory” behind this framework and its ill application.

Fig. 2.4 – The Three Overlapping Circles of Sustainability. Source: Adapted from (Adams 2006)

The next and final representation, the Embedded Circles, also known as the Three Nested Circles, has a completely different approach to the sustainability problem. The TLS and TOC frameworks differ in the interaction among the three dimensions but keep the necessary equality between them. However, in the Embedded Circles this equality is completely overthrown and instead it is replaced by a priority chain, "with the economy dependent on society and environment while human existence and society are dependent on, and within the environment" (Giddings, Hopwood, and O'brien 2002). Following this reasoning, it is clear that most society activities influence or are influenced by the natural environment and that the economy can be identified as a subset of society. This can be easily perceived in nowadays society considering that the development of industry, business, production and technology are all linked to social interactions. This way, in Figure 2.5 it is possible to understand this hierarchical model consisting of three nested circles, hence the name. It should be noted that society, although with some restrictions, would exist without economy, and the environment would still prosper if society and economy perish (Lovelock 2000).

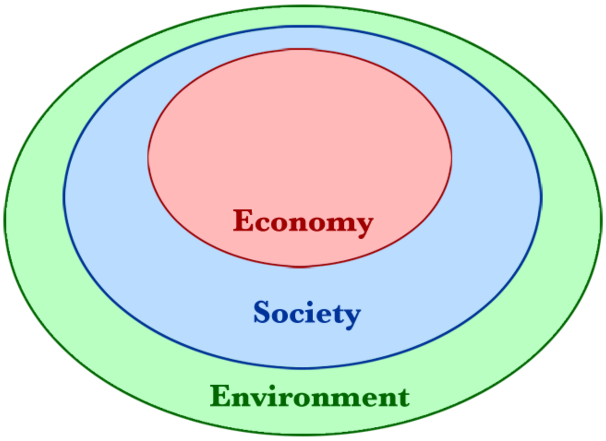

Fig. 2.5 – The Three Nested Circles. Source: Adapted from (Adams 2006)

2.3.3. The Natural Step

The Natural Step (TNS) is a non-profit organization founded by Dr. Karl Henrik Robèrt, a Swedish oncologist, in 1989. Following the publication of the Brundtland Report in 1987, the TNS aimed to “create a shared language so that we may work together for effective and desirable change”, offering processes and tools to more quickly achieve true sustainability. To do so, TNS pioneered the “Backcasting from Principles”, creating the “ABCD Process” as shown in Figure 2.6 (Holmberg and Robèrt 2000).

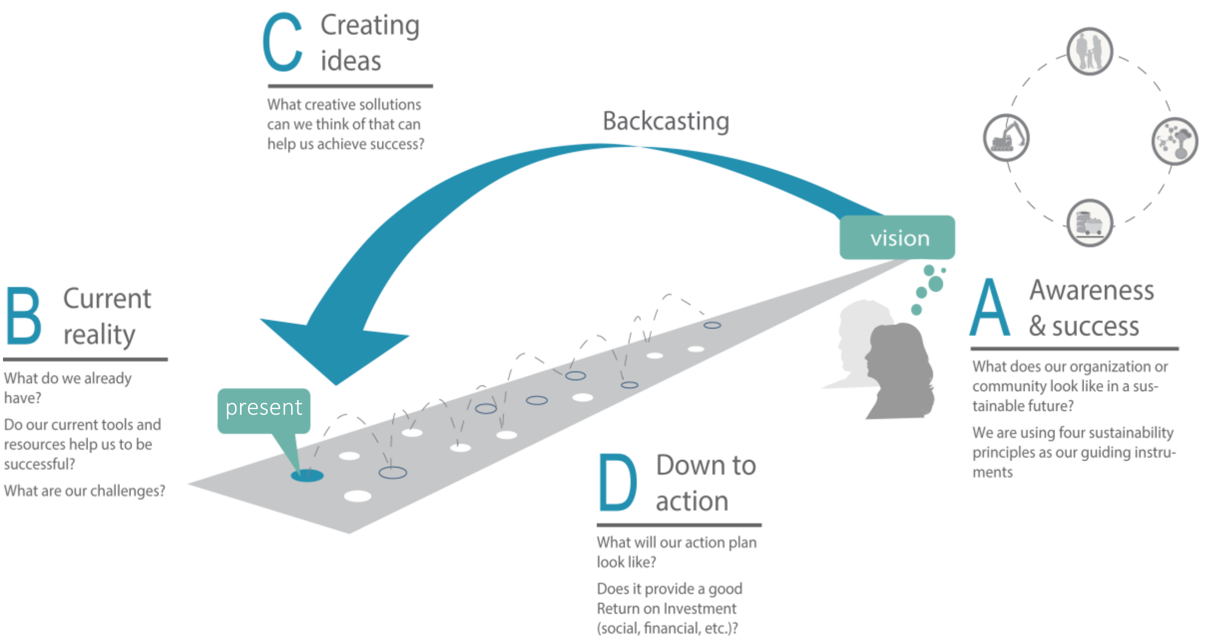

Fig. 2.6 – The “ABCD Process” for Backcasting. Source: adapted from (TNS 2011)

These “tools” are based on four scientifically derived “System Conditions” which where reworded as The Four Sustainable Principles, listed on TNS official website (TNS 2016):

1. **Condition:** *In a sustainable society, nature is not subject to systematically increasing concentrations of substances extracted from the Earth’s crust.* **Principle:** *To become a sustainable society we must eliminate our contribution to the systematic increase of concentrations of substances extracted from the* Earth’s *crust.*

In this first principle, it is stated that the mining of minerals and metals or the burning of fossil fuels will not happen at a speed that creates a systematic increase of these substances in the ecosphere. This is to prevent that the ecosystems and its living organisms won’t be adversely affected by the increasing exposure to these substances. Problems addressed by this principle include metal toxicity (i.e. lead and mercury), contamination of surface and groundwater (i.e. fuels spills) and, the most known problem, the increase in greenhouse gases leading to global climate change. In the end, this first principle requires the implementation of comprehensive metal and mineral recycling programs as well as a decrease over fossil fuels dependence.

2. **Condition:** *In a sustainable society, nature is not subject to systematically increasing concentrations of substances produced by society.* **Principle:** *To become a sustainable society we must eliminate our contribution to the systematic increase of concentrations of substances produced by society.*

This principle is much similar to the first principle, the difference being the nature of the substance increasing in concentration. In a sustainable society substances such as dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyl (PCB), and chlorofluorocarbons (CFC) must be reduced, finding solution to decrease its dependence. The most prominent problem addressed by this principle is caused by this last synthetic organic compound, which is responsible for the ozone layer depletion, increasing the ultraviolet radiation in the troposphere and growing the risk of cancer.

3. **Condition:** *In a sustainable society, nature is not subject to systematically increasing degradation by physical means.* **Principle:** *To become a sustainable society we must eliminate our contribution to the systematic physical degradation of nature and natural processes.*

The third principle acknowledges the manipulation and destruction of the ecosystems and, subsequently, the services they provide. It states that for a society to achieve true sustainability it is necessary to bar the systematical impoverishment of our ecosystems applying a consumption rate that doesn't affect it or stopping its degradation all at once. In the book *Nature is services: societal dependence on natural ecosystems,* Gretchen Daily describes "ecosystem services" as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" (Daily 1997). From this description it is clear that the preservation of our natural habitats and its biodiversity provides the necessary tools for a sustainable environment ensuring its longevity and endurance. Some problems addressed by this principle are over harvesting, habitat destruction and overfishing.

4. **Condition:** *In a sustainable society, people are not subject to conditions that systematically undermine their capacity to meet their needs.* **Principle:** *To become a sustainable society we must eliminate our contribution to conditions that systematically undermine people's capacity to meet their basic human needs.*

In this last Principle is stated that there cannot be environmental sustainability without social sustainability. In other words, meeting the requirements for the fourth Principle is a necessity to evade infringing the first three. In the matter regarding this forth condition Vicki Robin states: "System condition four is essential because we are humans. No humans, and system conditions one, two, and three would likely not be challenged. We are the agents, the ones making choices that are compromising the fabric of life" (Dominguez and Robin 1992). This is easily supported by nowadays society. "In a sustainable society resources are used fairly and efficiently in order to meet basic human needs globally" (Kibert 2008), however we are faced with a world where the richest 1% of the world population owns more than 48% of the global wealth (Credit Suisse 2015) and more than 3 billion people are malnourished (Pimentel and Wilson 2004). Dr. Karl-Henrik Robèrt, founder of TNS, explains, "From a systems perspective, the fourth system condition divides into two major parts – the technical and the social." The technical part can be interpreted as "technical reduction of resource throughputs", in other words, eliminating waste, applying the 3R Policy, being efficient. The social part can be translated into the fairness concerning "all aspects of human needs in relation to each unit of resources used by society." Dr. Robèrt goes on to explain, "the two parts of the fourth system condition allow for two methods of improvement. We can reduce the throughput of resources for the same utility unit (satisfaction of human kind), or we can increase the utility unit (satisfaction of human kind) per resource throughput. The best result is, of course, if we can do both at the same time" (Rosenblum 2000).

Finally, added to the Principles already stated, TNS provides a system for corporations to fundamentally trail the four system Principles. This system relies on a set of levels through which a corporation progresses by achieving the necessary goals imposed by each level. Doing so, the corporation increases their impact on attaining a sustainable society. This will not only increase the company performance, saving resources and improving staff satisfaction, but also improve marketing, accountability and transparency.

Some of the levels goals are:

- Reduce emission;
- Use recycled materials;
- Decrease materials extraction;
- Increase efficiency;
- Increase employers satisfaction;
- Among others.

In the last few years TNS has become a well-known and accepted framework transmitting the consequences society will endure if not changed, while also delivering the necessary objectives to address this change (Kibert *et al.* 2011).

2.3.4. Corporate Social Responsibility

"Corporate Social Responsibility is the continuing commitment by business to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society at large" (Watts and Holme 1999). In the last few years environmental mishaps, fraud, and corporate scandals such as "the Exxon Valdez oil spill, the Bhopal disaster, the fraudulent financial reporting and subsequent collapse of Enron, Tyco, and Worldcom, and the 2008-2009 collapse of financial industries, destroyed public trust and confidence in the corporate world," (Kibert *et al.* 2011) affecting the credibility, performance, and profit of various corporations whose behavior and financial reporting could not be trusted. This compelled multiple stakeholder groups, employees, suppliers, customers, community groups, and governments, to pressure managers in dedicating resources to Corporate Social Responsibility (CSR) (McWilliams, Siegel, and Wright 2006). As a result, this ideology turned itself into a reality, driving many to consider that companies should have a positive social impact in their communities (Lichtenstein, Drumwright, and Braig 2004, Lindgreen and Swaen 2010).

In its core CSR is the idea that business corporations have an obligation to work for social betterment (Frederick 1986) going "beyond the interests of the firm and that which is required by law" (McWilliams, Siegel, and Wright 2006). As such, some CSR actions include recycling, waste management, water management, abating pollution, supporting local businesses, events and charities, human resource management programs, among others. These actions are endorsed and well greeted by the consumers while amoral attitudes and behaviors are unaccepted, potentially impacting the well-being of the corporation (Fields 2002).

Up to the end of the 1980's top level companies saw CSR mainly has a public relations tactic to ensure public support (Burt 1983). Hardly ever CSR was applied consciously without profit being the main purpose behind its implementation. In fact, most managers ranging from the low-mid level corporations considered this framework to damage the financial performance of a company, thus paying little to no attention to CSR (Ackerman 1973). Nonetheless, by the late 1990s, CSR was being encouraged and endorsed by governments, private companies and consumers. Most major organizations such as the "United Nations, World Bank, Organization of Economic Co-operation and Development and International Labor Organization not only endorse CSR, but have also established guidelines and permanently staffed divisions to research and promote CSR" (Lee 2008). This change in behavior was so evident that between 1977 and 1998 almost 200% more companies from the *Fortune 500* began mentioning CSR as an essential component to their organization's goals (Boli and Hartsuiker 2001). Former CEO of Hewlett-Packard (HP), Carly Fiorina, described this change as a "new reality of business" (Fiorina 2001) and the Chairman and CEO of General Electric, Jeffrey R. Immelt stated that "the world has changed" (Gunther 2004, Lee 2008).

Companies embracing the CSR attain significant benefits such as a better marketing and brand status (McWilliams and Siegel 2000, Werther and Chandler 2005, Maheshwari and Kumar 2013), reduced liability, and better chances of obtaining a 'license to operate' within communities where these companies need to establish operations (Dahlsrud 2008, Yates and Horvath 2013). Other benefits include a greater diversity of stakeholders (Donaldson and Preston 1995, Freeman 1984, Bansal and Bogner 2002) and a better reputation within current and future employees (Bhattacharya, Sen, and Korschun 2008, Korschun, Bhattacharya, and Swain 2014). These efforts practiced by major companies determine a separation between the conventional model of doing business with the sole purpose of profiting and a trend toward including social awareness and sustainability in business (Kibert *et al.* 2011).

CSR has been criticized by numerous managers, economist and scholars for being essentially self-serving (Matten, Crane, and Chapple 2003, Windsor 2001, Ihlen, Bartlett, and May 2011). One well defended critic is that the adoption of this framework is done with the primarily objective of improving public relations (Mullerat 2010, Heath 2010, Castka *et al.* 2004, Lepoutre and Heene 2006, Banerjee 2008, Ciliberti, Pontrandolfo, and Scozzi 2008, Johnson, Scholes, and Whittington 2008), projecting a supposedly large positive impact on the community with close to no effort (Aras and Crowther 2012, Mullerat 2010). Other critics rely in the fact that some companies such as chemical, oil and tobacco companies, or even weapons manufactures, engaging in CSR activities contradict their own products and practices (Mullerat 2010, Fernando 2011). Finally, there is enough evidence showing how markets do not automatically punish companies that do not uphold the CSR framework. "Unethical stocks" are still stocks (Bendell and Bendell 2007).

2.4. Green Building Construction

2.4.1. Sustainable Design and Environmental Building Performance Assessments

As seen previously, sustainability impacts and embraces all aspects of human life. The established frameworks shown in the last section of this chapter are evidence that much work and thought has been giving on the matter, and measures have been taken to ensure the achievement of a sustainable society (Ebert, Essig, and Hauser 2011). In this sense, the construction and building industry accounts not only for a substantial fraction of the overall environmental impacts but also for the sustainable actions taken by society (Junnila and Horvath 2003), having extensive direct and indirect impact on the environment. During design, construction, occupancy, maintenance, renovation, and demolition, buildings consume energy, water, and raw materials, produce waste, and emit potentially dangerous atmospheric emissions (Vierra 2014). In fact, in the United States, the construction industry accounts for over 40% of the energy consumption, 65% of electricity, 30% of greenhouse gas emissions, 30% of raw material use, and 136 million tons of waste output annually. (Cidell and Beata 2009)

However, with the rise in public awareness, society became more sensitive to this industry contribution to environmental issues. As such, making use of public opinion, and as seen in section 2.2 and 2.3, sustainability pursuers prompted a change in this behavior, pushing governments and institutions for the establishment of financial incentives, green building standards, certifications, and rating systems meant at mitigating the negative effects of the AEC Industry on the natural environment through sustainable design (Vierra 2014). Furthermore, with the growing awareness surrounding sustainable construction's potential to positively impact environmental issues, more scholars started conducting research on this area (Robichaud and Anantatmula 2010), more software marketed as green building design tools were created, and several equipment and building materials manufactures carefully prompted their products to help design teams acquiring a greener building (Gowri 2004).

As this push towards sustainable design improved and building performance became a major concern for professionals in the building industry (Crawley and Aho 1999), Energy Performance Certificates (EPCs), defining building quality in term of energy efficiency, increased both in popularity and importance throughout almost all Europe and America. However, these certificates did not correspond to a complete sustainability certification. In fact, sustainability certifications were lacking since this topic's complexity and lack of objectivity hindered the creation of a truly comprehensive assessment method (Ebert, Essig, and Hauser 2011). In fact, as previously stated, these certifications rely upon green design, which is defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) as "one that is aware of and respects nature and the natural order of things; it is a design that minimizes the negative human impacts on the natural surroundings, materials, resources, and processes that prevail in nature" (Grumman 2003), which is far too broad and philosophical a concept to be implemented and articulated into specific design objectives. As such, environmental building performance assessment emerged as one of the major issues in sustainable construction, propping discussions about what building performance is, according to different interest parties involved in building development (Cole 1998, Cooper 1999, Holmes and Hudson 2000).

This way, substantial work has gone into developing systems to evaluate a building's environmental performance over its life. These systems had the purpose of measuring how successful any development is with regards to balancing energy, environment and ecology, taking into account both the social and technology aspects of projects (Clements-Croome 2004).

2.4.2. BREEAM BASED CERTIFICATES

In 1990, the British Research Establishment developed BREEAM, the first of these green building rating systems for environmental performance assessment (Vierra 2014). This tool was created in collaboration with private developers from the United Kingdom and started as a credit system for new office buildings. However, along the years BREEAM has been continuously updated and extended to cover assessment of buildings such as existing offices, supermarkets, new homes, industrial buildings, schools, among others (Yates and Baldwin 1994). As such, BREEAM evolved from a subjective design checklist to a comprehensive assessment tool to be used in various stages of a building life cycle, asserting itself as the benchmark for assessing environmental performance in the United Kingdom, Canada, Australia, and several other countries (Grumman 2003).

In the years following its creation, sustainability certificates gained more supporters spawning many other assessment methods around the world based upon BREEAM (Ebert, Essig, and Hauser 2011). These quality seals integrate the full concept of sustainability, approaching topics such as water efficiency, energy consumption, material use, building location and indoor environmental quality (Azhar *et al.* 2011). However, although this primarily criteria is common among the different rating systems its scoring is heavily influenced by the type of building being study (Saraiva, Almeida, and Bragança 2015) and the "countries climatic, cultural and legal situations" (Ebert, Essig, and Hauser 2011). Consequently, this means that there are tens of certificate systems operative in different countries resulting in hundreds of this tools around the world. Currently, it is estimated that over 600 green product certifications exist around the world, with the number continuing to grow rapidly (Vierra 2014). The most important and internationally recognized systems can be found in Table 2.2.

Table 2.2 – Assessment tools and respective countries. Source: adapted from (Ebert, Essig, and Hauser 2011, Ding 2008)

COUNTRY	ASSESSMENT TOOL
Australia	NABERS, Green Star, ABGR, BASIX
Austria	Total Quality
Belgium	BREEAM Belgium
Brazil	LEED Brasil, AQUA, BREEAM Brasil
Canada	LEED Canada, Green Gloves, BEPAC
China	GBAS, Three Star, GHEM
Czech Republic	SBTool CZ
Finland	PromisE
France	HQE, Escale, BREEAM France
Germany	DGNB, BNB, TÜV Süd SCoRE
Great Britain	BREEAM, CPA, DQI
Hong Kong	CEPAS, HK-BEAM
India	LEED India, TGBRS India
Italy	Protocolo ITACA
Japan	CASBEE
Mexico	LEED Mexico, SICES
Netherlands	BREEAM Netherlands, Eco-Quantum
New Zealand	Green Star NZ
Poland	BREEAM Poland
Portugal	Lider A, SBTool Portugal
Russia	BREEAM Russia
Singapore	BCA, Singapore Green Mark
Spain	VERDE, BREEAM Spain
South Africa	SBAT, Green Star SA
Switzerland	MINERGIE
Taiwan	ABRI, EMGB
United Arab Emirates	LEED Emirates, BREEAM Gulfs
United States	LEED, Green Globes

In terms of the objectives normally associated with these certifications, the following four are typically the most coted (Ebert, Essig, and Hauser 2011):

- Make building sustainability transparent for society and economically feasible for investors and clients, while continually promoting and innovating these certificates and adjusting them to the most possible scenarios;
- Clearly and comprehensively define and describe the requirements of the criteria and objectives for sustainable buildings, creating guidelines to support clients and planning teams in their intention to erect a sustainable building;
- Make the application of these certification systems simple and not bothering for the design process. Sustainability will only gain further acceptance if building certifications maintain themselves feasible;
- Divulge and explain the advantages of sustainability certificates to stake holders, owners and users, removing the skepticism behind these certifications.

2.4.3. ADVANTAGES AND DISADVANTAGES

The reasons for obtaining a green building certification are varied. Normally, the most related advantages are linked with the environment, however, as it will be possible to understand in this section and in 2.5, these advantages can also display more social and economic characteristics. In fact, these certifications provide valuable educational and marketing tools, offering incentives for clients, owners, designers and users to highly prefer sustainable buildings. Numerous studies (Cassidy, Wright, and Flynn 2003, Ries *et al.* 2006) quantify profitability of green buildings, based on the improved operation efficiency, despite the potential for higher design and construction costs. Furthermore, studies demonstrate that occupants and workers increase in productivity and health when faced with a sustainable building, when compared with a standard commercial building (Vierra 2014). This is greatly attributed to a better indoor environment quality, increase in natural daylight, use of healthier materials and products, among others (Heerwagen 2000). In fact, a General Services Administration (GSA) study shows that of all the twelve sustainable buildings addressed, all cost less to operate, have excellent energy, water, waste, maintenance, recycling and transportation related performances, and occupants are more satisfied with the overall building than typical commercial buildings occupants (Fowler *et al.* 2008).

There are, however, significant drawbacks to sustainability certifications. In fact, the interaction between construction and the environment is still greatly unknown and every environmental building assessment has limitations that may hinder their future practicality, efficiency and effectiveness (Cole 1998).

Lowton argues that environmental matters should be considered as early as possible in the design phase in order to minimize environmental damage, reduce remedial costs and maximize financial return (Lowton 1997). This position is also supported by Crookes and de Wit (Crookes and de Wit 2002), who recognized the identification and preparation stages as the most efficient for these assessments. However, these certifications are currently designed to evaluate projects at a later stage, when it is already too late to consider correcting many environmental issues, which goes directly against the recommendations.

Another disadvantage, already briefly approached in this thesis, is the national or regional variations not accounted for into most assessments. In fact, regional, social, cultural and economic variations are too complex for a certification to cover. Such differences may include climatic conditions, income level, existing building materials and techniques, appreciation for historic value, among others (Kohler 1999).

Another well debated issue affecting these assessments is their complexity. In fact, since environmental sustainability is such an extensive and challenging to capture concept, most assessments tend to involve large quantities of detailed information to be assembled and analyzed, which is only worsened by the fact that this data includes quantitative and qualitative parameters (Cole 1998). As such, these rating systems tend to generalize most environmental criteria in order to remain simple, which jeopardizes the actual usefulness and precision of these certifications. As such, achieving the balance between effective coverage and simplicity of use is one of the most difficult quests for these certifications.

Finally, another disadvantage is the increase in upfront cost for the project design and building construction. Although this cost is normally redeemed during the building life cycle, the necessary investment needed to only perceive if it is possible to acquire a green certification is often significant, influencing owners to distance themselves from these certifications (Ding 2008).

2.4.4. Assessment Tool Typology

With this sudden rising in sustainability certifications, the ATHENA Institute has introduced a classification system, the "Assessment Tool Typology" (Haapio and Viitaniemi 2008), which is composed of three levels:

- Level 1: product comparison tools and information sources (i.e., BEES, TEAM);
- Level 2: whole building design or decision-support tools (i.e., ATHENA, Eco-Quantum);
- Level 3: whole building assessment frameworks or systems (i.e., BREEAM, SBTool).

In the following section, LEED, a level 3 assessment tool, will be introduced as the chosen certification to be further studied in this thesis. In this sense, it is important to refer that this tool was chosen not only by its notoriety, impact, and quality, but also by the amount of information available to the general public that concern its rating systems and scoring.

2.5. Leadership in Energy and Environmental Design

In the last section it was possible to determine that there are a rising number of initiatives that aim to encourage the building industry into being further environmentally responsible, fostering the integration of different innovative approaches into design of buildings which are safe for the environment and for those living or working there (Yudelson 2004, Dean 2003, Elizabeth and Adams 2000, Woolley *et al.* 2002, Spiegel and Meadows 2010). Among these strategies are the certification systems in which LEED is located. In the first chapter, it was stated that the designed software had the purpose to help not only achieve this certification but also, to some extent, automate its attainment. As such, to better understand this facet of the program, the following section will address this green building system, briefly exposing its history, the categories it is divided into, which topic it approaches, and how its rating system works.

LEED is a voluntary, consensus-based, rating system established by the United States Green Building Council (USGBC) to assess the environmental sustainability of buildings designs. Its main objective is to promote the "adoption of [high-performance,] sustainable green building and development practices" (Kok, McGraw, and Quigley 2011, Crespi *et al.* 2004), providing building owners and operators with an effective framework for identifying and applying practical and measurable green building design, construction, operation and maintenance solutions (USGBC 2005). This ideology is further defined by the LEED system goals or Impact Categories, represented in Figure 2.7.

Fig. 2.7 – LEED Impact Categories. Source: (Owens *et al.* 2013)

Through this certification a building can attain four different rating levels: LEED Certified (40-49 points), Silver (50-59 points), Gold (60-79 points), and Platinum (80-100 points). As of the end of 2007, from the entire buildings certified through LEED, 34% were LEED Certified, 32% were Silver, 28% were Gold and 6% were Platinum. These statistics clearly demonstrate the ambition from the AEC Industry to have higher impact on the society's sustainability, instead of settling themselves for the minimum requirements (Cidell 2009).

To achieve these levels the candidate projects must satisfy all the prerequisites and the respectively necessary number of points. In total there are 110 possible points to amass in the form of a straightforward checklist. These points are grouped into 9 key areas, also known as categories (Owens *et al.* 2013, Humbert *et al.* 2007):

- Integrative Process;
- Location and Transport;
- Sustainable Sites;
- Water Efficiency;
- Energy and Atmosphere;
- Materials and Resources;
- Indoor Environmental Quality;
- Innovation;
- Regional Priority.

These categories encompass topics such as: site impact on natural ecosystems and natural resources; travel distance to near communities; public infrastructures; employment opportunities and recreation facilities; conservation of wetlands and water bodies; access to different quality means of transportation;

compact development; existence of local natural food production and improved nutrition; building energy performance; water management; pollution prevention during construction; rainwater management; solar orientation; employment of renewable energies; application of recycled or reused materials; and light pollution (USGBC 2016b).

In order to calculate these points, LEED subdivided each category in building categories, such as, New Constructions, Schools, Hospitals, Data Centers, Homes, among others. This provides LEED with the necessary flexibility to be able to certificate most building-types (Farham and Gholian 2014). During construction, supporting documentation and evidence are compiled and submitted to USGBC, who determines, based on that information, whether or not to award the point (Azhar *et al.* 2011). Since much of this information is incredibly scientific oriented, builders and designers often hire “LEED accredited professionals” to help in the process of certification.

Since its single pilot project in 1998, LEED multiple ratings system has turned into a dominant force in the commercial and institutional building market in the United States. Many cities and even states have reviewed their building codes to require new public buildings to meet certain LEED performance standards, with multiple municipalities including minimum LEED certifications for new commercial construction and/or renovations (Kok, McGraw, and Quigley 2011). However, this scenario is not restrained to the US alone. After its introduction in 2000, the market diffusion and popularity of LEED green building certification has been gradually increasing all over the world, fact most noticeable in recent years (Scofield 2013). Currently, over 30 countries are directly connected to LEED and more than 155 countries and territories contain LEED projects within their borders (USGBC 2016c). Today, LEED is internationally recognized as a quality brand for the owners, manufacturers and users of buildings, providing new methods of designing, constructing and operating buildings along the nature of the so-called "Green Building” (Farham and Gholian 2014).

LEED benefits are widely recognized and most meet the ones already stated in 2.4.3. As such, these benefits are also normally related to the environmental and human health aspects of society. However, recent studies demonstrate economic benefits surrounding green buildings. Although there is a slight increase in the upfront cost of the building (average of 2%), the results on the life cycle savings exceed, on average, 20% of the total construction cost, meaning a return on investment superior to 10 times in approximately 2 to 13 years depending on the certification level (Kats *et al.* 2003, Farham and Gholian 2014). This return period can be greatly reduced depending on the amount of social and economic incentives attributed by governments (Crespi *et al.* 2004). Furthermore, LEED increments the CSR of a company, improving its marketing and attracting stakeholders, resulting in an average 3.5% increase in occupancy and 3% in rent (Vierra 2014).

Throughout their 16-years history, LEED has remained one of the most, if not the most, accepted benchmark for designating “green buildings” around the world. Its ability to remain flexible thanks to the input of designers, builders, environmentalists, among others, allows the incorporation of new building types in each released version, while also modifying the existing standards to better address the different countries geographic, economic and social aspects (Cidell 2009).

Table 2.3 – LEED

<table>
<tr><th colspan="36">LEED</th></tr>
<tr><td colspan="36">Implemented across over 155 countries and territories</td></tr>
<tr><th colspan="36">Certification Level</th></tr>
<tr><td colspan="36">Checklist: 110 points</td></tr>
<tr><td colspan="9">LEED Certified
(40 – 49 points)</td><td colspan="9">Silver
(50 – 59 points)</td><td colspan="9">Gold
(60 – 69 points)</td><td colspan="9">Platinum
(80-110 points)</td></tr>
<tr><th colspan="36">Categories</th></tr>
<tr><td colspan="4">Integrative Process</td><td colspan="4">Location and Transport</td><td colspan="4">Sustainable Sites</td><td colspan="4">Water Efficiency</td><td colspan="4">Energy and Atmosphere</td><td colspan="4">Materials and Resources</td><td colspan="4">Indoor Environmental Quality</td><td colspan="4">Innovation</td><td colspan="4">Regional Priority</td></tr>
<tr><th colspan="36">Building Categories</th></tr>
<tr><td colspan="3">New Construction</td><td colspan="3">Core and Shell</td><td colspan="2">Schools</td><td colspan="2">Retail</td><td colspan="2">Healthcare</td><td colspan="2">Data Centers</td><td colspan="2">Hospitality</td><td colspan="4">Warehouses & Distribution Centers</td><td colspan="2">Homes</td><td colspan="3">Multifamily Midrise</td><td colspan="3">Commercial Interiors</td><td colspan="3">Existing Buildings</td><td colspan="3">Plan</td><td colspan="2">Built Project</td></tr>
</table>

2.6. STORMWATER RUNOFF

As seen in the last section, and as established in Table 2.3, LEED covers a broad length of concepts evidenced by its numerous Categories. One particular Category, the "Sustainable Sites", rewards decisions about the environment surrounding a given building. This Category emphasizes the vital relationships among buildings, ecosystems, and ecosystem services, focusing in preserving biodiversity and habitat conditions, mitigating light and sound pollution, and managing rainwater runoff (USGBC 2016b). As such, with the intent of connecting BIM and Sustainability through the automation of LEED, the credits associated with managing the rainwater runoff were chosen as an example. This way, the concepts related to these credits are explained in the following section. It should be stressed, that in the author's opinion, these credits are amongst the hardest to automate since they cover a wide variety of topics as it will be possible to see in the following section.

2.6.1. EFFECTS OF URBANIZATION IN STORMWATER QUANTITY

The percentage of urban population worldwide is steadily increasing (UNDP 2008). As such, urban areas are continuously expanding in terms of space and density. As an area urbanizes, streets, sidewalks, parking lots and buildings cover and compact the soil while also removing natural vegetation. As such, one side effect of this urbanization is the increase of impermeable surfaces. Rainfall no longer soaks into the ground as readily as before, increasing the runoff volume and the speed at which it flows (Livingston and McCarron 1992). This has numerous consequences for the city infrastructure and neighboring environment (Berndtsson 2010).

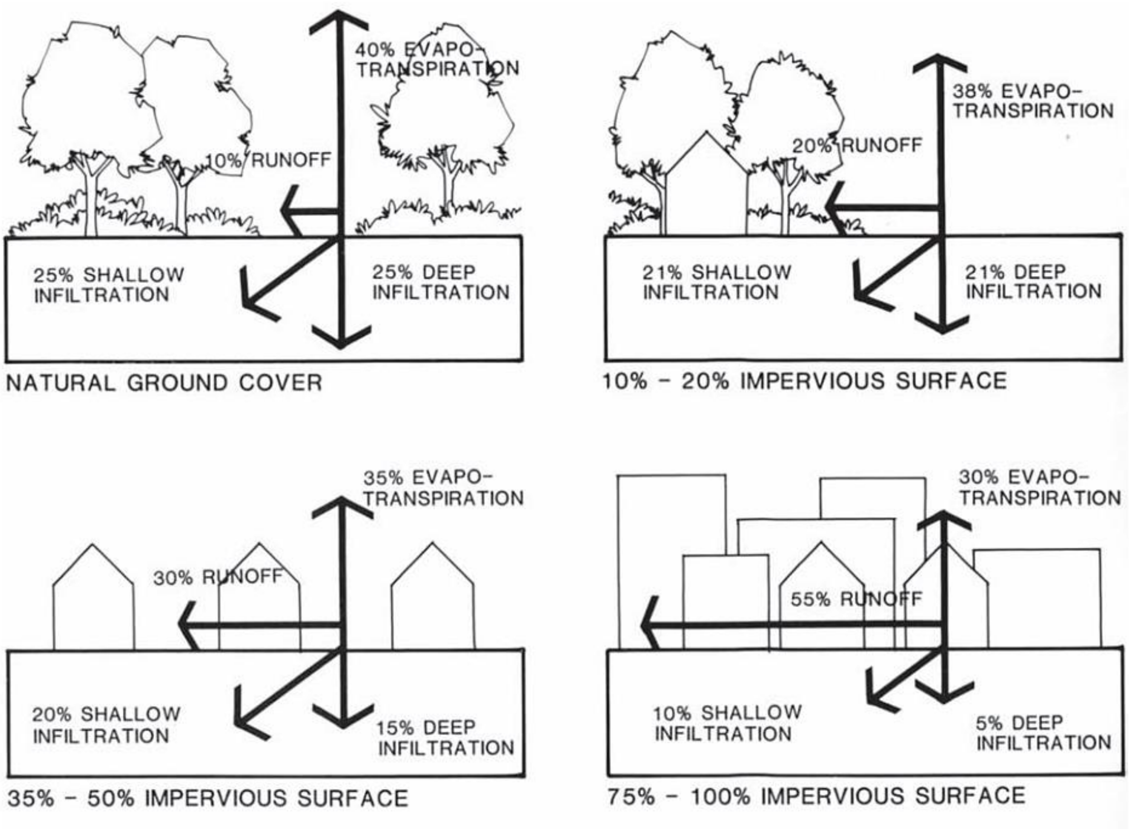

Fig. 2.8 – Average changes in runoff flows depending on the total percentage of paved surfaces. Source: adapted from (Livingston and McCarron 1992)

As seen in Figure 2.8, the impact the rainfall runoff has on ecosystems is exacerbated by this urbanization. Since infiltration decreases, the stress on existing stormwater infrastructure rises alongside the runoff peaks and runoff volumes (Leopold 1968). This in turn creates severe problems in a large number of urban areas such as increased flooding and ecological damage to urban streams (Thurston 2006). In fact, proliferation of impervious surfaces allows rainfall water to reach stream faster and at higher speeds, which causes higher peak flows, creates stream alterations, enhances channel erosion, deposition of sediments and habitat degradation. This results in even more problems such as structures being undermined, homes being damaged, recreational areas being threatened and aesthetic values being destroyed (Livingston and McCarron 1992). Also, since impervious surface stops water from infiltrating the soil, less water is available for groundwater recharge, which reduces stream base flow and creates groundwater recharge deficits.

2.6.2. EFFECTS OF URBANIZATION OF STORMWATER QUALITY

Land use is undoubtedly linked to water quality. In an undeveloped area, natural, physical, chemical, and biological processes come together to gather and reuse most of the materials in stormwater. However, as human land use increases, these processes are disrupted and daily activities add materials to the land surface (Livingston and McCarron 1992). As such, depending on the land use inside the watershed, nutrients, toxics, and suspended materials, among others, can be loaded on the runoff from roadways, parking lots, and other infrastructures. Leaves, litter, animal wastes, oil, greases, heavy metals, fertilizers, and pesticides are transported overland into waterways causing toxic loading on the natural stream (Brabec, Schulte, and Richards 2002, Klein 1979). This way, rainfall runoff can not only be a main pollution problem but also a potential pollution source (Arnold Jr and Gibbons 1996).

Following this reasoning, (Arnold Jr and Gibbons 1996) recommended “imperviousness” to be used as an indicator for stream health. As such, after this publication many complex predictors of stream impacts were proposed. One example of these predictors is the multimeric urban index, which comprises numerous infrastructure, socioeconomic, and land cover variables. These studies shown that the total percentage of impervious area correlated highly (R^2 = 0.96) with stream health, suggesting imperviousness as an effective predictor of stream impacts and, by far, the simplest (Coles *et al.* 2004).

2.6.3. Low-Impact Development Best Managing Practices

Conventional stormwater infrastructure, which is still predominant in urbanized areas, is intended to quickly convey water from the city to natural recipients (Ferguson 1994). With this purpose, conveyance infrastructures that centralize runoff are vital. However, these structures do not contribute to correct the problems enumerated in the previous paragraphs, since they only serve as pathways for the runoff (Dietz and Clausen 2008), neglecting other vital factors such as water pollution, off-site damage because of accelerated flow, or even the loss of water resources (Livingston and McCarron 1992). Still, stormwater agencies kept emphasizing centralized solutions despite the growing emphasis on water quality. This is greatly attributed to the economic scale advantages these larger solution offer when compared with smaller decentralized solutions capable of filtrating water (Cutter *et al.* 2008).

However, when the idea of sustainable development acquired more ground in the early 1990s, the urban water infrastructure was targeted to major rethinking. Nowadays stormwater is recognized as an important resource to be used for social benefitted and from which advantages should be frequently extracted, treating and reusing it before conveying it to natural streams (Jia *et al.* 2012). With this intent, Low-Impact Development (LID) Best Managing Practices (BMP) should be implemented.

LID-BMP are a fairly new approach at stormwater management (Montalto *et al.* 2007). Pioneered in the early 1990s in Prince George’s County, Maryland (Coffman and France 2002), LID-BMP are basically measures for mitigating nonpoint source pollution caused mainly by stormwater runoff (Zhen *et al.* 2006). These measures goal is to mimic the pre-development site hydrology, including the runoff peaks, volumes, and composition, in the post-developed site conditions (Dietz and Clausen 2008). To do so, these LID-BMP intend to store rainfall through long periods of time, reusing it, infiltrating it, or simply evaporating it, after which it is slowly released into the stream. While conventional stormwater infrastructure pipe water to low spots as swiftly as possible, “LID-BMP uses micro-scale techniques to manage precipitation-generated runoff as close to where it hits the ground as possible” (Zhen *et al.* 2006). With this purpose, LID–BMP implementation should be entirely coordinated with the local construction plan and integrated, if possible, into the site landscaping scheme. In order to achieve this goal these measures need to be designed into the earliest phases of the project (Jia *et al.* 2012).

Although decentralized LID-BMP cannot provide similar large scale economic advantages as centralized facilities, they do not require large contiguous land areas. These measures can be located on parcels with fairly low marginal land use value thus successfully reducing the total installation cost. This is mostly beneficial in urban areas where land values can be overwhelming (Cutter *et al.* 2008). Furthermore, fairly simple economic encouragement policies can be implemented as incentives for installations by private landowners, either in a fee/rebate system (Thurston 2006) or a tradable allowance system (Thurston *et al.* 2003). Evidence of such successful incentives can be seen in the Portland’s

Downspout Disconnect Program, introduced in 1993, where residents were offered 53$ as an incentive to redirect their roof runoff to their lawns and gardens. By 2005, more than 47,000 homeowners had redirected their runoff, roughly eliminating 4.2 million cubic meters of stormwater runoff per year (Portland 2006). Lastly, LID-BMP were documented to effectively moderate potential climate impacts, increasing urban resilience to future climate change (Gill *et al.* 2007).

LID-BMP can be categorized into two different groups: structural and non-structural. Structural LID-BMP comprise engineered and built systems aimed at controlling water quantity and/or quality (Martin, Ruperd, and Legret 2007). These are centered in either rainwater retention, detention or filtration (Wahl 2009):

- Retention – the stormwater is consumed onsite. This is typically done by transpiration through plants, evaporation, or soil infiltration. The ability of LID-BMP to retain stormwater is primarily dependent on the existing vegetation, the soil configuration and the actual available space;
- Detention – the stormwater is stored and slowly released, preventing high peak flows from stressing stormwater infrastructures and eroding riverbanks. Detention is normally achieved by either spreading the stormwater over a larger area or lengthening its route to the final natural recipient by conveying it through further LID-BMP features;
- Filtration – the stormwater is cleaned either by filtration through non-organic media (i.e. sand), sedimentation, or elimination of pollutants using microorganisms and vegetation. The first alternative is most effective at removing particles containing phosphorus and heavy metals, while the latter is better suited to deal with soluble pollutants.

Non-structural LID-BMP comprise a range of "pollution prevention, education, management and development practices" (Martin, Ruperd, and Legret 2007) intended to impede the transformation of rainfall into runoff (Elliott and Trowsdale 2007). This thesis focusses on structural LID-BMP, including several measures such as: green roofs, rain barrels, cisterns, permeable paving, rain gardens and swales. In the following sub-sections these LID-BMP are presented, in order to better understand their application in the designed software.

However, before the actual detailing of these measures, it should be stressed that there are a few more LID-BMP strategies which will not be mentioned in this thesis. These remaining infrastructures are more concerned with stormwater runoff quality and ways to pursue its treatment, instead of answering retention and detention problems. Despite most of the remaining strategies end up absorbing and slowing a small part of the runoff, since it is such a small percentage and since the proposed software particularly focusses in the actual quantity and not quality of the runoff (although some attention is given to the latter), LID-BMP such as filter strips were not approached. Also, LID-BMP that cover huge areas, such as wetlands, were also not taken into consideration since the software targets small and medium sized LID-BMP that can actually be implemented in most types of buildings. Larger management methods such as wetlands are mostly used to drain huge areas, which are currently not modelled in BIM and are thus beyond the scope of this work.

2.6.3.1. Green Roofs

Historically, engineered green roofs were originated in northern Europe, where sod roofs and walls have been used as construction techniques for hundreds of years (Low Impact Development Center 2007). However, the contemporary approach to green roofs started in the late 1970s in the urban areas of Germany (Köhler 2003).

The huge amount of impervious areas and the high land prices in urban regions make the creation of green areas in these regions an expensive or even impossible task (Ferguson 1998). However, given the enormous amount of idle roof areas (approximately 40 to 50% of all impermeable surfaces in urban areas (Dunnett and Kingsbury 2004)), green roofs, also known as vegetated roof covers, eco-roofs and nature roofs, were labeled as an interesting and promising alternative (Mentens, Raes, and Hermy 2006). Nowadays, in other greatly urbanized societies like Japan, Switzerland, Singapore and Belgium, green roofs have already resulted in incentives from the government to encourage or even impose the use of green roofs (Osmundson 1999, Wong *et al.* 2003, Dunnett and Kingsbury 2004).

This multi-beneficial infrastructures helps manage stormwater runoff by reducing its volume and augmenting its quality by retaining and filtering stormwater in the plant's soil and root uptake zone. It has been estimated that green roofs, in comparison to conventional roofs, can reduce cadmium, copper and lead in runoff by over 95 percent and zinc by 16 percent. Nitrogen levels can also be diminished (Chicago 2003). As for the volume reduction, it comprises three stages and can be clearly noticed in Figure 2.9 (Mentens, Raes, and Hermy 2006):

- Delaying the original time for the runoff due to absorption;
- Mitigating the total runoff by retaining most of the absorbed water;
- Slowly release the excess water (stored in the pores of the substrate) over long periods of time as runoff.

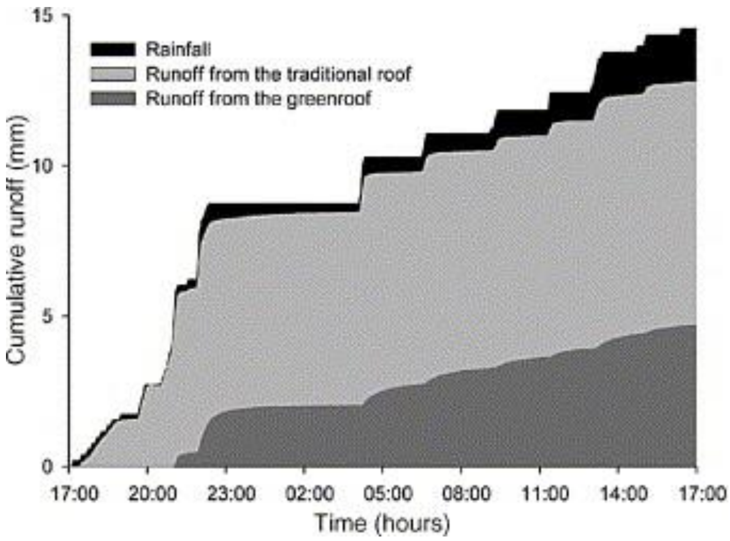

Fig. 2.9 – Typical cumulative runoff from a non-green roof and an extensive green roof as observed in Leuven (Belgium) during the 24h period of a 14.6 mm (April 2003). Source: (Mentens, Raes, and Hermy 2006)

Most green roofs are typically composed by four main layers: a vegetation layer, a lightweight soil media (where water is retained and in which the vegetation is anchored), an underlining drainage layer (to evacuate the excess water), and a high quality impermeable membrane to protect the building structure. The soil is carefully planted with a selected combination of plants prepared to endure the harsh weather conditions of roofs while still accomplishing their runoff related purposes (Low Impact Development Center 2007). A typical green roof constitution can be seen in Figure 2.10.

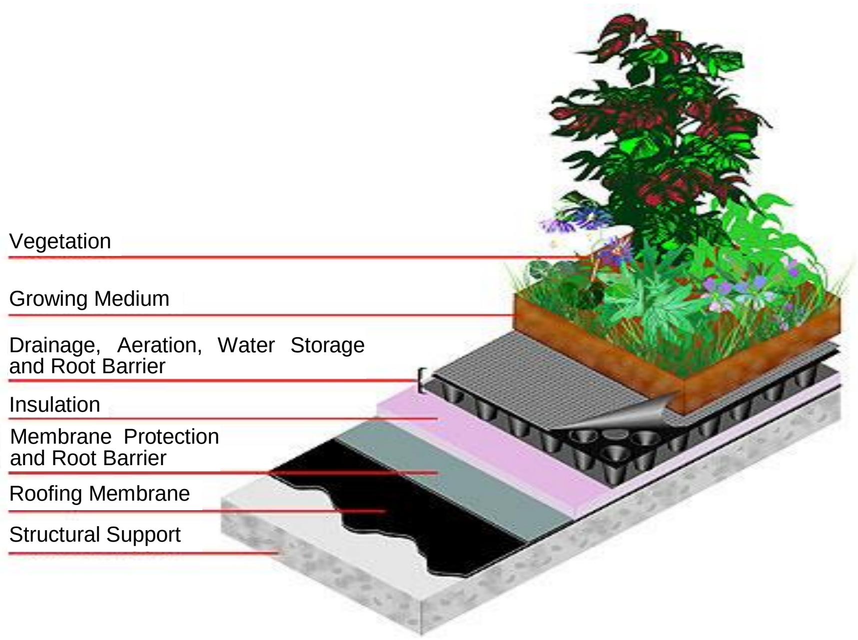

Fig. 2.10 – Typical green roof constitution. Source: (Chicago 2003)

When implementing a green roof, special attention should be given to the structural and load-bearing capabilities of the building, waterproofing, drainage and storage systems (Chicago 2003). Also, the amount of stormwater retained may slightly vary depending on many factors, such as: volume and intensity of the rainfall, spent time since the previous rainfall event, depth and wetting scale of the substrate layer, slope of the roof, age of the roof, quality of the maintenance, and typology of the utilized plants (Teemusk and Mander 2007). Typically, lower slopes and increased media result in larger retention values (Dietz 2007).

In Table 2.4, it has been estimated that green roofs intercept between 60 and 85% of rooftop runoff, which results in proposed runoff coefficients for green roofs varying between 0.1 and 0.5 (Dietz 2007).

Table 2.4 – Summary of green roof precipitation retention

LOCATION	PRECIPITATION RETENTION (%)	REFERENCE
Augustenborg, Sweden	63.0	(Bengtsson, Grahn, and Olsson 2005)
Illinois, USA	65.0	(Scholz-Barth 2001)
North Carolina, USA	64.0	(Hathaway, Hunt, and Jennings 2008)
Pennsylvania, USA	70.0	(Bliss, Neufeld, and Ries 2009)
Auckland, New Zealand	82.0	(Voyde, Fassman, and Simcock 2010)
Michigan, USA	68.0	(Carpenter and Kaluvakolanu 2010)
Michigan, USA	69.8	(VanWoert *et al.* 2005)
Michigan, USA	70.7	(VanWoert *et al.* 2005)
Michigan, USA	65.9	(VanWoert *et al.* 2005)
Michigan, USA	68.1	(VanWoert *et al.* 2005)
Oregon, USA	69.0	(Hutchinson *et al.* 2003)
North Carolina, USA	62.0	(Moran, Hunt, and Jennings 2004)
North Carolina, USA	63.0	(Moran, Hunt, and Jennings 2004)

In addition to the stormwater quantity and quality benefits, green roofs may also extend the life of roofs two to three times, since the vegetation prevents the roof from being exposed to ultraviolet radiation and cold winds, moderating the temperature extremes. Also, these infrastructures further insulate the building both acoustically and thermally, reducing energy costs for cooling and/or heating the building (Van Renterghem and Botteldooren 2009, Takakura, Kitade, and Goto 2000, Niachou *et al.* 2001). They can help preserve habitat and biodiversity in an otherwise sterile urban environment while also improving air quality by contributing to reduce the "heat island" effect of urban areas through increasing evapotranspiration (Bass *et al.* 2002). Finally, they may even provide food, garden areas and attractive views, improving esthetic value.

By focusing on the thickness of the substrate layer, the maintenance needed and the slope angle, two central types of green roofs are usually distinguished (Mentens, Raes, and Hermy 2006, Chicago 2003):

- Extensive systems – comprised of 50 to 100 millimeters of soil, these green roofs are typically planted with dense, low-growing, drought-resistant vegetation with shallow root systems and can achieve up to 55-200 kilograms per square meter of roof area. They are normally easily maintainable and provide insulation and stormwater absorption. The slope angle can be as high as 45º;
- Intensive systems – similar to gardens, these green roofs are comprised of 150 to 300 millimeters of soil and can achieve 350 to 700 kilograms per square meter of roof area. They host deeper-rooted plants, including grass, flowers, shrubs, and even trees. As such, these systems provide more maintenance but also more benefits, such as: insulation, water filtration, storage, and increased habitat opportunities. The slope angle must be inferior to 10º.

- Applicability:

Green roofs can be applied both in new building design and rehabilitation projects. However, special attention must be given to the load-bearing capacities of the roof. These systems can be applied to most residential, commercial, industrial and institutional properties (Chicago 2003).

- Maintenance considerations:

After establishing the green roof, maintenance requirements are usually minimal and similar to the classic maintenance required by a typical garden such as watering and weed removal. The only big differences are the regular inspections to the roof membrane and drainage flow paths (Chicago 2003).

- Cost considerations:

Green roofs prices may vary greatly between countries and types (intensive/extensive). In this research, values were found to typically range between 75 and 235€ per square meter, with an average of 150€ per square meter (Chicago 2003, Lake Superior Streams 2009, Peck and Kuhn 2003, Low Impact Development Center 2007, PADEP 2006, Montalto *et al.* 2007). These values already include operation, maintenance and repair costs.

2.6.3.2. Rain Barrels/Cisterns

Rain barrels and cisterns are efficient, low-cost, easily maintainable retention and detention devices that may be applied into either residential, commercial or industrial sites in order to manage rooftop runoff (Low Impact Development Center 2007). These water storage vessels can be located aboveground (rain barrels or cisterns) or underground (cisterns only) to effectively capture and store the runoff from a building's roof by connecting themselves to the gutter and downspout system (Lake Superior Streams 2009). The stored water can then be retained for long periods of time and reused when needed, unless it is a heavy rainfall, in which case it may be required to slowly release the water over time (PADEP 2006).

Fig. 2.11 – Rain barrels. Source: adapted from (PADEP 2006)

As seen in Figure 2.11, for residential applications rain barrels display a traditionally simple design which include a hole at the top, connecting to the downspout, a sealed lid, an overflow pipe and a spigot at or near the bottom of the barrel. In concordance with the last paragraph, the spigot can either be left closed to retain the water or partially open to let it be slowly released. For commercial and industrial uses, rain barrels are typically larger and may include pumps and filtration devices. (Low Impact Development Center 2007) Cistern are similar in design but normally tend to display bigger dimensions.

The efficiency and effectiveness of either rain barrels or cisterns is traditionally dependent on two aspects. The first is the relation between their storage volume and the size of the roof. For instance, taking into account a simple residential building with a 110 square meter roof, it should possess four 208-liter barrels to retain an equivalent runoff of about 7.5 millimeters. Despite this volume not being noticeable when faced with larger storms, if used alongside other LID-BMP it could make the necessary difference. Also it can considerably reduce direct runoff originated from smaller storms. The second aspect is the actual drainage of the rain barrels (i.e. for irrigation) which, in the best case, should be fully empty when the next storm hits (Chicago 2003).

- Applicability:

Rain barrels and cisterns are appropriate where the stored water can be used efficiently or released to adequate landscaping or vegetation. As previously stated, these vessels can be applied to most residential, commercial, industrial and institutional properties (Chicago 2003). The primary benefit linked to this devices beyond runoff quantity and quality management is the possibility for reducing water utility costs, by reusing the stored water.

- Maintenance considerations:

Maintenance regarding rain barrels and cisterns are typically simple. Periodical cleaning may be necessary to remove debris (i.e. leaves) originated from the rooftop. In the case of installed pumps and filter devices, these must also be target of proper maintenance. To avoid mosquito breeding and water freezing, the barrel should be sealed during warmer months and drained prior to winter (Chicago 2003).

- Cost considerations:

Ready-made rain barrels can vary from 17.5 to 175€, averaging 110€ for a 208-liter barrel (Montalto *et al.* 2007, Brown, Gerston, and Colley 2005, PADEP 2006, Chicago 2003). These values already amount for operation, maintenance and repair costs. However, given its simplicity, homeowners can greatly reduce costs by making their own devices.

2.6.3.3. Permeable Paving

Permeable paving refers to paving materials that promote onsite absorption of rain and snowmelt, resulting in a reduce runoff leaving the area (Chicago 2003). These systems facilitate the storage and infiltration of rainfall into the soil, or other subsurface storage, reducing peak discharge rates and runoff volumes (Montalto *et al.* 2007). These materials can further contribute to eliminating stormwater related problems such as standing water, water pollution, groundwater recharge, site aesthetical damage, erosion of streambeds and riverbanks, pavement glare, and automobile hydroplaning accidents (Lake Superior Streams 2009, Low Impact Development Center 2007). Permeable paving may also increase aesthetic and marketing advantages over conventional paving, depending on the materials selected. For example, vegetated pavers could substantially improve the aesthetic appeal of paved areas while also reducing the “urban heat island” effect (Chicago 2003).

Pervious pavement typically comprises a permeable surface course (either block pavers, plastic grid systems, porous asphalts, or porous concretes (Dietz 2007)), underlined by a uniformly-graded stone bed, which offers provisional storage in its void for peak rate control, followed by a uncompacted soil mantle to which the stormwater is slowly drained. Occasionally, the stone bed can hold an overflow control device in order to better control peak rates when faced with larger storm events. A layer of geotextile filter fabric splits the aggregate and the underlying soil, stopping the migration of most pollutants to the bed (PADEP 2006). A typical permeable paving can be seen in Figure 2.12.

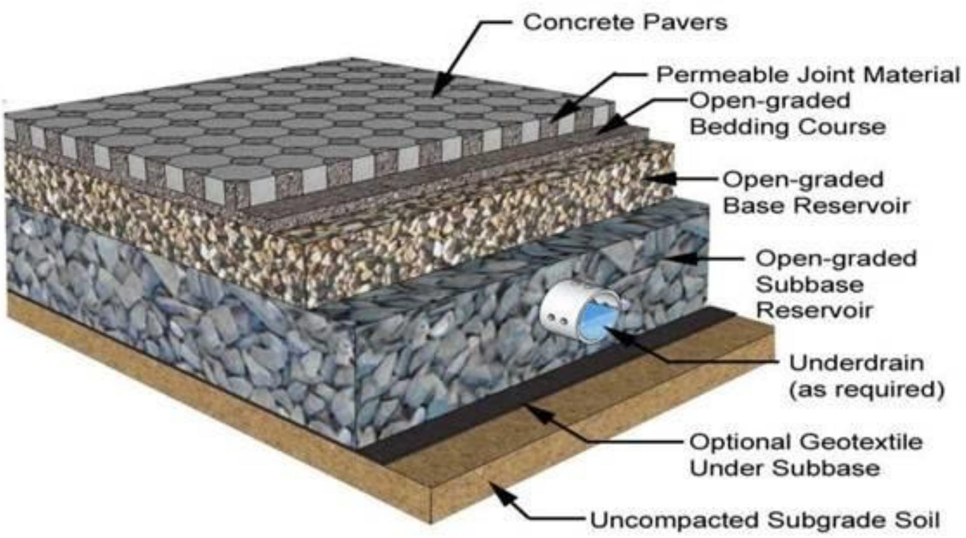

Fig. 2.12 – Typical green roof constitution. Source: (PADEP 2006)

As already stated, permeable paving also reduces the pollutants carried by the stormwater runoff, impressively mitigating concentrations of metals (i.e. Lead (Pb), Copper (Cu), Cadmium (Cd), and Zinc (Zn)), suspended solids, oil, grease and bacteria by approximately 94 to 99% (Legret, Colandini, and Le Marc 1996, Legret and Colandini 1999, Pagotto, Legret, and Le Cloirec 2000, Rushton 2001, Bill Hunt, Scott Stevens, and David Mayes 2002, Dierkes, Holte, and Geiger 1999, Fach and Geiger 2005, Dreelin, Fowler, and Carroll 2006, Tota-Maharaj and Scholz 2010, Myers, Beecham, and van Leeuwen 2011, Pezzaniti, Beecham, and Kandasamy 2009). These same studies also demonstrate a 60 to 90% reduction is runoff volume, which are typically associated with an estimated runoff coefficient of 0.12 to 0.4 (Montalto *et al.* 2007, Ferguson 2005). In major cities of Japan, the use of permeable paving is reported to be responsible for a 15–20% reduction in peak rates of runoff (Watanabe 1995).

- Applicability:

Permeable paving is gaining acceptance and being particularly applied in playgrounds, plazas, sidewalks, parking lots, utility and access roads, emergency access lanes, fire lanes and alleys (USEPA 1999, Ferguson 2005, Chicago 2003).

- Maintenance considerations:

The main objective for maintenance in pervious pavements is to prevent the surface and/or underlying infiltration bed from being clogged with fine sediments. As such, to preserve and prolong the system's life span, the surface should be vacuumed biannually. Vegetated paving blocks may also require occasional mowing (PADEP 2006).

- Cost considerations:

Cost regarding permeable paving are greatly connected with the porous material used. As such, cost can range from 110 to 300% of a typical standard asphalt paving. However, most of these costs are normally regained as maintenance (permeable paving requires less frequent replacement) and related stormwater infrastructure, such as curbs, gutters and storm sewers, which may not be required when applying permeable paving. In this research, values were found to typically range between 20 and 130€ per square meter, averaging 65€ per square meter (Montalto *et al.* 2007, PADEP 2006, USEPA 1999, Chicago 2003). These values already amount for operation, maintenance and repair costs.

2.6.3.4. Rain Garden/Swales

Rain gardens and swales both work in the same manner with only magnitude and location being the difference between these two LID-BMP. In fact, while rain gardens are usually grown in small residential infrastructures to collect the roof runoff, swales are generally connected to larger commercial settings and impervious areas such as parking lots or roadways (SSSA 2016).

Both methods normally mimic a bioretention system, and consist of a shallow, landscaped depressions filled with specific planted vegetation that can survive in rainwater soaked soil (Chicago 2003). This vegetation is typically comprised of native plants and wild flowers, shrubs, perennials, and sometimes even trees. Typically used to promote absorption, evapotranspiration and infiltration of stormwater runoff in order to reduce runoff speed and volumes, these management practices can also be very effective at pollutant treatment, reduce peak flow, decrease soil erosion, increase groundwater recharge, enhance aesthetical value, and preserve habitat and biodiversity (Anyona 2009).

The system behind these methods is quite simple. The runoff velocity is first reduced in the grass strip. Then the water is momentarily contained on the surface while suspended solids and sediment are filtered and settled at the mulch layer. Followed by a slow travel to the plant/soil/microbe media for infiltration, storage and pollutant removal. And finally, the water enters the bed which provides additional volume control (PADEP 2006).

Fig. 2.13 – Rain Garden. Source: (SSSA 2016)

Fig. 2.14 – Swale. Source: (SSSA 2016)

The pollutant treatment highly depends on the soil mixture, vegetation selection and slope inclination (Dietz 2007, Dietz and Clausen 2005, Davis 2008, Davis *et al.* 2009). Research focused on this topic typically describes these types of bioretentions as excellent removals of heavy metals, with concentration reduction superior to 95% for Cu, Pb and Zn. Nutrient concentration are also reduced with phosphorus, Kjeldhl-nitrogen and ammonia-nitrogen achieving reduction rates of 80, 68 and 87%, respectively. Finally, suspended solids, bacteria, oil and grease also display high retention rates, achieving a retaining value of 86% for the suspended soils, 99% for bacteria and 67% for both oil and grease (Davis *et al.* 2003, Dietz and Clausen 2006, Roseen *et al.* 2006, Hunt *et al.* 2006, Hunt and Lord 2006, Low Impact Development Center 2007). These researches also contributed with some preliminary data concerning thermal pollution mitigation through the decrease of runoff temperature.

Reduction of runoff volumes and peak flow rate using rain gardens and swales is also well documented (Davis 2008, Davis *et al.* 2009, Dietz 2007, Line and Hunt 2009, Chapman and Horner 2010, DeBusk and Wynn 2011, Roy-Poirier, Champagne, and Filion 2010). These research show a range of 40 to 99%, with conclusions regarding the retention dependence mainly focusing on the magnitude of rainfall events, slope inclination, soil compaction and chosen vegetation. However, most studies show that for small events, these bioretention systems can readily capture the entire runoff inflow volume.

- Applicability:

Since these measures allow for a flexible design layout, they can be applied in most residential and commercial landscapes (Dietz 2007). Suggested applications include implementation in: roads sideways, parking lot islands, residential gardens, and even agricultural water quality improvement (DeBusk and Wynn 2011, Chicago 2003).

- Maintenance considerations:

These LID-BMP require a relatively low maintenance when compared with sewer systems. Still, they include periodic inspection to guarantee the system is functioning properly, along with management of the vegetation (weeding, reestablishing plants, among others). If a practice fails due to clogging, rehabilitative maintenance will restore it to proper operation. Incorporating pretreatment helps to reduce the maintenance burden on these systems and reduces the likelihood that the soil bed will clog over time (Chicago 2003).

- Cost considerations:

Rain gardens and swales costs can greatly vary depending on the design procedure, chosen plants, control structures, soil conditions, land prices, size, among others. Based on this thesis research, costs can range between 25 and 380€ per square meter, normally averaging between 130€ per square meter (Chicago 2003, Bannerman 2003, Lake Superior Streams 2009, Montalto *et al.* 2007). However, if planned correctly, these measures remain effective for over 20 years and, just as permeable pavements, normally regain their initial investment as maintenance, which requires inferior costs when compared with other stormwater infrastructures that would be necessary if these LID-BMP measures were not applied.

2.7. THE RATIONAL METHOD

Now that the means to actually reduce the stormwater runoff were thoroughly described, it is necessary to actually understand how the stormwater runoff produced onsite is calculated. As such, returning to the LEED directive on these credits, LEED directs its users to the *Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects* from the United States Environmental

Protection Agency (USEPA 2009). There, the user is presented with a series of runoff estimation methods such as the TR-55 and the Rational Method to choose from. Although the TR-55 has a higher precision, it also requires a greater volume of input data. As such, since the proposed software pursues an easy and simple way of obtaining the runoff, the Rational Method was chosen.

The Rational Method has been applied for over 100 years to estimate peak runoff rates from rather small, highly developed drainage areas (PADEP 2006). The application of this method is based on a single simple formula that relates the runoff generating potential of the watershed, with the watershed drainage area and the average rainfall intensity for a certain length of time (the concentration time). Although being a simple and straightforward method, approximating both the concentration time and the runoff coefficient creates substantial uncertainty in the calculated peak runoff rate (Thompson 2007). However, despite this uncertainty, this method remains the most used for runoff calculation. As such, the formula goes as follows:

$$Q = C \times I \times A \tag{2.1}$$

Where:

Q = peak runoff rate (cubic meter per second);

C = runoff coefficient (dimensionless);

I = average maximum rainfall intensity (mm/h);

A = watershed drainage area (square meter).

Of the three variables to obtain for this formula, two are quite straightforward: the watershed drainage area and the runoff coefficient. The first, is easily obtained through an array of different alternatives that range from actual onsite measurement to Revit project properties. The second, is obtained through tabulations linked to the building land use. These tabulations, as well as the values used in the software, can be found in Attachment A, B and C.

However, to obtain the final variable (rainfall intensity), while still following the LEED suggested bibliography (USEPA 2009), the user is met with the need to determine the 95th percentile rainfall event for a minimum of ten years of local storm data. Although this information is easily acquirable for the United States through sites such as the National Climatic Data Center, the same cannot be said for most other countries. As such, as it was already stated, since the proposed software pursues simplicity, this 95th percentile was replaced by the average maximum rainfall intensity. This change was made since this data is obtained through intensity-duration-frequency (IDF) curves, which are easily available for most countries, and also because the retrieved value for the average maximum rainfall intensity for a 10 years period (used time span) does not stray away from this 95th percentile, sometimes even staying above it. As such, by using these values, the software user can obtain a realistic runoff. It should be stressed that although this is the default intensity for the software, the used values can always be overridden if the user wants to use different values. This can be done, for example, if the actual 95th percentile is obtained or any other intensity than the average maximum rainfall has to be computed.

However, these IDF curves greatly differ from country to country and, as such, a country as to be selected as an example to be used alongside the software. Since the building chosen for the case study is located in Portugal, this was the selected country. The word “example” should be stressed since users can easily access the database and modify it by, for example, introducing other countries’ information.

Finally, after selecting the country, the software can correctly calculate the runoff of a building site by using equation 2.2 and the presented values in Table 2.5.

$$I = a \times t^{b} \tag{2.2}$$

Where:

I = average maximum rainfall intensity (mm/h) for the duration t (min);

a, b = constants dependent on the return period (Table 2.5).

Table 2.5 – Constants *a* and *b* dependent on the return period and pluviometric region. Source: adapted from (Portugal. Laws 1995)

Regions	A		B		C	
T (years)	*a*	*b*	*a*	*b*	*a*	*b*
2	202.72	-0.577	162.18	-0.577	243.26	-0.577
5	259.26	-0.562	207.41	-0.562	311.11	-0.562
10	290.68	-0.549	232.21	-0.549	348.82	-0.549
20	317.74	-0.538	254.19	-0.538	382.29	-0.538
50	349.54	-0.524	279.63	-0.524	419.45	-0.524
100	365.62	-0.508	292.50	-0.508	434.75	-0.508

Both the equation and Table 2.5 can be found in *Regulamento Geral dos Sistemas Públicos e Prediais de Distribuição de Água e de Drenagem de Águas Residuais* (Portugal. Laws 1995) and both are obtained from the IDF curves. In fact, Table 2.5 values are obtained through the pluviometric regions, also known as rainfall regions, rainfall zones, or rain regions, whose boundaries are defined by the IDF curves. These zones typically divide a country’s territory which, in the case of Portugal, means obtaining three different zones, as shown in Figure 2.15: region A, B and C.

The values shown in Table 2.5 for region A are acquired from the IDF curves for Lisbon, while the values for regions B and C are obtained by, respectively, decreasing and increasing 20% to the values from region A. These zones include the following locations:

- Pluviometric region A – comprises all the zones not referenced in B and C;
- Pluviometric region B – comprises the municipalities of *Alfândega da Fé*, *Alijó*, *Almeida*, *Boticas*, *Bragança*, *Carrazeda de Ansiães*, *Chaves*, *Figueira de Castelo Rodrigo*, *Freixo de Espada à Cinta*, *Macedo de Cavaleiros, Meda*, *Miranda do Douro*, *Mirandela*, *Mogadouro*, *Montalegre*, *Murça*, *Penedono*, *Pinhel*, *Ribeira de Pena*, *Sabrosa*, *Santa Marta de Penaguião*, *São João da Pesqueira*, *Sernancelhe*, *Tabuaço*, *Torre de Moncorvo*, *Trancoso*, *Valpaços*, *Vila Flor*, *Vila Pouca de Aguiar*, *Vila Nova de Foz Côa*, *Vila Real*, *Vimioso* and *Vinhais*;

- Pluviometric region C – comprises all the municipalities of *Açores* and *Madeira* Special Administrative Regions, the councils of *Guarda, Manteigas, Moimenta da Beira, Sabugal* and *Tarouca,* plus all the areas located at an altitude superior to 700 meters in the councils of *Aguiar da Beira*, *Amarante*, *Arcos de Valdevez*, *Arganil*, *Arouca*, *Castanheira de Pera*, *Castro Daire*, *Celorico da Beira*, *Cinfães*, *Covilhã*, *Fundão*, *Góis*, *Gouveia*, *Lamego*, *Marvão*, *Melgaço*, *Oleiros*, *Pampilhosa da Serra*, *Ponte da Barca*, *Resende*, *Seia*, *S. Pedro do Sul*, *Terras do Bouro*, *Tondela*, *Vale de Cambra*, *Vila Nova de Paiva* and *Vouzela.*

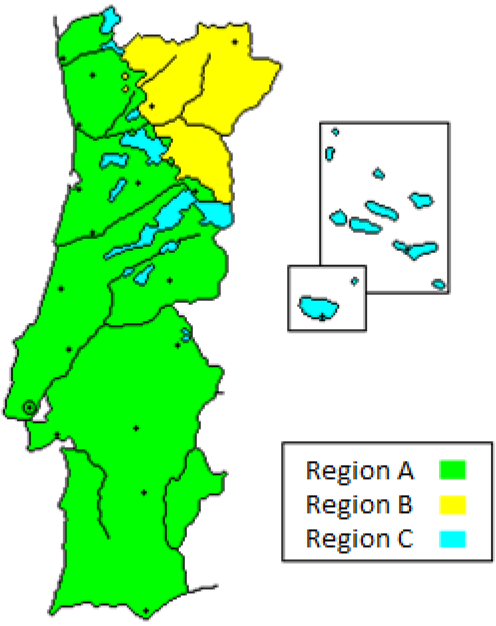

Fig. 2.15– Portugal pluviometric regions. Source: adapted from (SA 2012)

The actual intensity data used for the software can, once again, be found in Attachment A and B.

3
BUILDING INFORMATION MODELING

3.1. WHAT IS BIM?

As mentioned in this work's introduction, the second large concept approached in this thesis is Building Information Modeling, most commonly known as BIM. The first notions related to BIM emerged in the 1970's and are credited to Professor Charles M. Eastman, from the Georgia Institute of Technology (Eastman *et al.* 1974). However, the exact term *Building Information Model* would only appear in an article by G. A. van Nederveen, in 1992 (Van Nederveen and Tolman 1992), and would only become popular, in conjugation with its acronym *BIM*, 10 years later when *Autodesk* released a white paper entitled *Building Information Modeling* to describe four dimensional (4D) representation in the AEC Industry (Autodesk 2002).

BIM is defined as the process of "generating, storing, managing, exchanging, and sharing building information in an interoperable and reusable way" (Vanlande, Nicolle, and Cruz 2008, Eadie *et al.* 2013). It "is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" (NBIMSPC 2016). In the last few years since BIM was introduced to the AEC Industry, this idea has gone from a scholar concept to the centerpiece of this industry, encompassing all phases of a building project: planning, design, construction, operation and, finally, demolition of the building (Eastman, Liston, *et al.* 2011, Azhar 2011). This revolutionary concept is one of the most promising advances in recent years for the AEC Industry, making it possible to create an accurate virtual representation of a building, also known as a *building information model*, with all the needed data attached to it (Azhar 2011, Sacks *et al.* 2010). Nowadays, BIM is believed to be indispensable to the AEC Industry in order to manage, share and exchange information among every entity related to a project such as engineers, contractors, architects, owners and facility managers (Eastman 1999, Fu *et al.* 2006).

Most of the world's leading AEC corporations have already left behind their earlier, drawing-based, CAD technologies and embraced BIM in most of their projects (Eastman, Liston, *et al.* 2011). This was a natural step to the AEC Industry since BIM has made its way into national policies (BIMIWG 2011). In fact, guidelines such as the *United Kingdom Publicy Available Specification PASS 1192* and the *State of Ohio BIM Protocol* presented the intent for local construction industries to change to a new framework where BIM was its center piece. In countries like Singapore, the United Kingdom and the Special Administrative Region of Hong Kong, BIM is even mandatory and in Germany, Spain, Australia, among others, its implementation in buildings projects will also be required in the following years. However, this transition is not easily implemented. In *BIM Handbook*, Eastman states "BIM is not just a technology change, but also a process change. By enabling a building to be represented by intelligent objects that carry detailed information about themselves and also understand their relationship with other objects in the building model, BIM not only changes how building drawings and visualizations are created, but also dramatically alters all of the key processes involved in putting a building together" (Eastman, Liston*, et al.* 2011). This was further supported by Howard and Björk (Howard and Björk 2008).

In the following sections it will be possible to approach the concept of BIM Dimensions, quickly explaining each dimension purpose, their impact on the AEC Industry, how this impact has and is expected to evolve in the next few years, and finally situating the proposed solution in one of this dimensions. Topics such as BIM advantages, disadvantages and maturity levels will be less addressed than a typical BIM related work since these subjects have already been thoroughly discussed (Eastman, Eastman*, et al.* 2011, Azhar 2011, Succar 2009).

Lastly, these dimensions are characterized by the capability to assemble buildings virtual models utilizing machine-readable parametric objects which display an adequate behavior depending on the necessity to design, analyze, or test a building (Sacks, Eastman, and Lee 2004). This way, models that only consist of a building three-dimensional replica without being expressed as objects with form, function, behavior, or any other data attached to it, will not be considered building information models (Tolman 1999).

3.2. BIM DIMENSIONS

BIM comprises further dimensions other than three dimensional (3D) modeling thus, when characterizing BIM, some attention has to be given to its dimensions (Smith 2014). These dimensions can be thought has categories. Each category has a purpose, a set of information that can be attained through it if the building information model attains the necessary conditions to be able to provide it (Kamardeen 2010). However, there is not an exact number of dimensions in BIM. This is mainly attributed to the fact that each dimension provides different complementary information, resulting in the terms *nD BIM* and *nD Model* so popularized in the last few years and which many companies try to achieve (Banks 2012, Fu *et al.* 2006). Although this representation of BIM seams quite simple, its analysis is further from that. Beyond the world of BIM, and by definition, each dimension contains the dimensions prior to its number. For instance, a 3D representation of an object should be extractable from a 4D model. However, a building information model could encompass seven dimensional (7D) information without offering five dimensional (5D) or six dimensional (6D) data. Finally, since the discussion between what 6D and 7D represent is still ongoing, this work will be addressing 6D as Sustainability and 7D as Facility Management (FM).

In this section it will be possible to understand the information each dimension provides, their unique purposes, and review the efforts towards their development. However, only the most commonly used dimensions of BIM will be addressed: 3D, 4D, 5D, 6D and 7D.

3.2.1. 3D BIM

This is the simplest, easiest and most used dimension of BIM. With 3D BIM it is possible to obtain a 3D spatial visualization of the building in study enabling clash detection, easiest implementation of prefabrication and lean techniques, two dimensional (2D) CAD automatic drawing, earlier collaboration of multiple design disciplines, among others.

3D modeling has been an important study topic since the 1960s. The capacity to illustrate polyhedral forms compositions for viewing was initially devised in the late 1960s with the potential to include it in industries such as the AEC, filming, gamming, along with others. These polyhedral forms could be composed into an image with a restricted set of parameterized and scalable shapes but editing and modifying complex shapes was not possible (Eastman, Liston*, et al.* 2011). However, in the mid-1970s the work of Bruce Baumgart (Baumgart 1973), Ian Braid (Braid 1974), Ari Requicha and Herb Voelcker (Requicha and Voelcker 1983), led to the creation of *solid modeling*. This technology then developed the first generation of practical 3D modeling design tools to which 3D BIM could be applied.

3.2.2. 4D BIM

4D BIM relates the solid 3D model with *time* in order to obtain information related to the building schedule (Jacobi 2011, McKinney, Kunz, and Fischer 1998). Linking this attribute to the model allows the attachment of information acquired through standard project management tools, such as, PERT and Gantt charts, to display every activity since the mobilization and site clearing to the finishing works (Kamat and Martinez 2001). This visual link between the schedule and construction site then enables optimal decision making during planning and construction, achieving proper activities linkage, workspace logistics, and feasible resource allocation, which includes labor, material, equipment and the use of the site space (Chau, Anson, and Zhang 2004, McKinney, Kunz, and Fischer 1998).

Efforts towards 4D planning models where first documented in 1990, by Retik et al., when studying the viability of applying computer graphics in association with construction to represent the building progress by the means of graphical images at any phase of construction (Retik, Warszawski, and Banai 1990). Later in 1996, Williams devised a demand-driven 4D model for the creation of a graphical construction plan on the basis of simulation, visualization, and communication (Williams 1996). In the same year, a case study on the San Mateo County Hospital applied visual-based 4D modeling and scheduling (Collier and Fischer 1996), and McKinney et al. devised a 4D computer-aided design tool with both visual and communicative functions to ease the design process (McKinney *et al.* 1996). In the following year, Adjei-Kumi and Retik utilized a library-based 4D model to virtually visualize the construction plan (Adjei-Kumi and Retik 1997), and in 1998, McKinney et al. again further innovated this topic, by establishing the ability to recognize construction issues prior to their actual occurrence by means of 4D-CAD models and the implementation of 4D models in software such as *Primavera* and *AutoCAD* (McKinney, Kunz, and Fischer 1998). Finally, in the turn of the millennium, Zhang et al. designed a 3D visualization model with schedule information for construction components (Zhang, Anson, and Wang 2000) and Kamat and Martinez developed a 3D visualization model capable of representing the entire process of a building construction (Shah and Dawood 2008, Chau, Anson, and Zhang 2004, Kamat and Martinez 2001).

3.2.3. 5D BIM

Over 60% of construction failures are due to economic factors, mostly because of lack of liquidity on daily activities (Russell and Jaselskis 1992). This problem is simply solved by linking cost information to the traditional 3D model and scheduling, also known as 5D BIM (Mitchell 2012, Kim *et al.* 2010, Sattineni and Macdonald 2014). This dimension allows the instant creation of financial estimations against time (Kamardeen 2010), greatly reducing the time consuming task of quantifying resources and estimating costs from days to minutes while also minimizing errors (Forgues *et al.* 2012).

The first attempts at cash flow forecasting in the early stages of a design project were first proposed by Reinschmidt, Frank (Reinschmidt and Frank 1976) and Sears (Sears 1981). To do so, the schedule and items costs had to be introduced manually. However, since this procedure was time-consuming, a fixed percentage of the project's total cost was attributed to each item type (Ashley and Teicholz 1977). This in turn diminished the procedure accuracy, which weakened the model in conjugation with the lack of accounting for lag between cost payments (Navon 1996).

However, more accurate cash flow forecasting procedures were proposed along the new few years (Kaka 1996, Kenley and Wilson 1986, Tucker 1986, Navon 1996, Boussabaine and Kaka 1998, Miskawi 1989), each going a step further and integrating delays on payments, budget constraints and available credit lines (Barbosa and Pimentel 2001), cash inflows, cash outflows, and overdraft size (Hegazy and Ersahin 2001), risk factors analysis (Hwee and Tiong 2002), changes in contractual conditions (Park, Han, and Russell 2005), integration of project financing and stochastic simulation-based scheduling (Lee, Lim, and Arditi 2011), among others.

With the conjugation of scheduling and 3D CAD models (Griffi, O'Brien, and Bronner 1990), other data such as costs started being linked to BIM (Feng, Chen, and Huang 2010, Kang and Paulson 1998, Liston, Fischer, and Kunz 1998, Waly and Thabet 2003). In 1999, Staub and Fisher (Staub and Fischer 1999) established the practical needs of incorporating time, cost, and scope, designing a method to determine cost at the activity level using 5D BIM. Feng et al. (Feng, Chen, and Huang 2010) automated the scheduling process and generated time–cost integration and finally, Liston et al. (Liston, Fischer, and Kunz 1998) introduced a visual decision support tool based on 4D BIM to determine how a proposed schedule change affected decision criteria such as cost (Lu, Won, and Cheng 2016).

This way, 5D BIM, can deliver advantages over traditional methods by rapidly and accurately updating both schedule and budget, improving construction details visualization, and determining risks in advance (Smith 2014, Lu, Won, and Cheng 2016, Sattineni and Macdonald 2014, Kala, Seppänen, and Stein 2010, Stanley and Thurnell 2014).

3.2.4. 6D BIM

Although prior to 7D, 6D is considered the youngest of BIM dimensions. Its appearance is greatly connected with the rising of sustainability awareness in the global context and, as such, encompasses all sustainability relationships between economic, social and environmental aspects of the AEC Industry. Consecutively, it has been argued that 6D could impact the other dimensions of BIM, not only because of its wide range of influence, but also because sustainability characteristics are likely to be subject to change over time (Kapogiannis, Gaterell, and Oulasoglou 2015). Hence, the necessity for a sustainability evaluation that addresses all life cycle stages of a building, namely material production, construction, operation, maintenance, demolition and disposal (Yung and Wang 2014).

Incorporating sustainability in the BIM model enables designers to meet carbon targets for specific elements of the project through life cycle analysis, determine triple bottom line impacts and performe energy analysis. It also allows an easier incorporation of daylighting, natural and mechanical ventilation, water efficiency, heat impact and renewable energies in the early stages of the building project. Lastly, it lets validate design decisions accordingly or test and compare different project options (Hardin 2009).

3.2.5. 7D BIM

FM is a wide concept attributed to everything from financial management to cleaning and maintenance of building systems, such as mechanical, electrical, plumbing, and fire protection (Atkin and Brooks 2009, Becerik-Gerber *et al.* 2011). It is aimed at energy saving, prolonging the lifespan of buildings, improving the satisfaction of future users and decreasing operating costs (Wang, Bulbul, and Lucas 2015). Although this process could easily be facilitated using BIM, "its use in post construction is still lagging", mainly because of the lack of experience by owners in BIM during the operation and maintenance phase (Giel and Issa 2014). However, recent studies prompted a drastic mentality change by estimating that lifecycle cost is five to seven times higher than the initial investment costs and three times the construction cost (Lee, An, and Yu 2012). This increased the recognition that BIM should be deployed to remain useful beyond the design and construction phase (Terreno *et al.* 2015).

The seventh dimension of BIM, FM, results from extending BIM into this post-occupancy period. 7D BIM creates a consolidated interface for a FM database concerning all aspects of building operational performance. This is possible as a result of the existing rich descriptions, relationships and property capabilities of each element provided by BIM, which facilitates its analysis and control (Kamardeen 2010, CRC 2007, McArthur 2015, Becerik-Gerber *et al.* 2011). As a result, tasks such as information management (Lucas, Bulbul, and Thabet 2013), substitution or reparation of equipment, improvement of comfort conditions (Becerik-Gerber *et al.* 2011), emergency management, energy monitoring and control, and even personnel training can be made both quicker and cheaper (Jordani 2010, Li, Calis, and Becerik-Gerber 2012, Teicholz 2013, Motamedi, Hammad, and Asen 2014, Dong, O'Neill, and Li 2014).

However, it is worth mentioning three current impediments to the correct implementation of 7D BIM: lack of knowledge about BIM from the facility owners (Giel and Issa 2014), data for FM being lacking or inadequate (Khemlani 2011), and issues concerning interoperability between BIM and current FM technologies (Akcamete *et al.* 2011). All BIM dimensions can be seen in Figure 3.1.

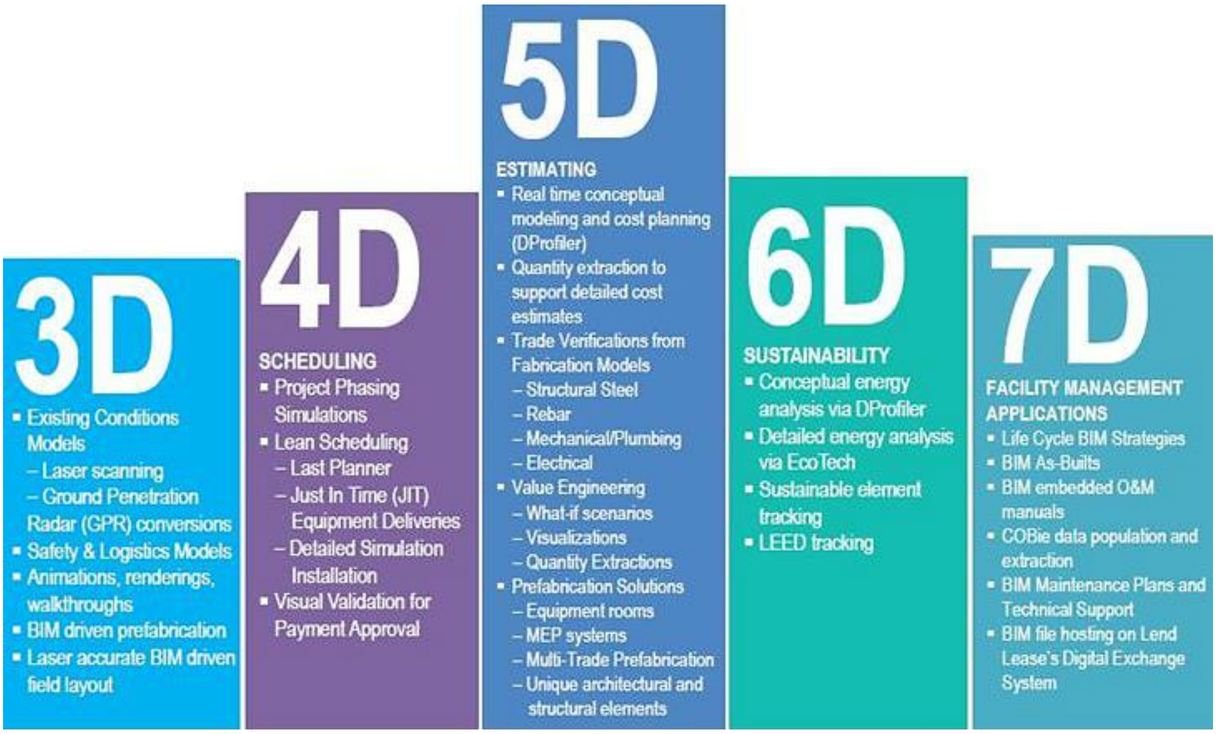

Fig. 3.1 – BIM dimensions. Source: adapted from (BIMTalk 2013)

3.2.6. THE IMPORTANCE OF EACH DIMENSION, ITS EVOLUTION AND BIM MATURITY LEVELS

The importance and impact each dimension had in the AEC Industry along the last few years varied greatly, not only because of the implementation of new dimensions each couple of years, but also because of the aptitude and knowledge BIM practitioners started to gain. In fact, as established by Figure 3.2, around the 1990s a BIM user would normally be located in level 0. This means only 2D CAD drafting was utilized. This was greatly attributed to the lack of innovation and sluggishness linked to the traditional AEC Industry. However, in the 2000s, as the majority of the market started working on level 1, 3D started to be significantly utilized in AEC Industry sharing its importance with 2D (Porwal and Hewage 2013). A few years later, in the beginning of the 2010s, 3D had asserted itself as the most used BIM dimensions. Nonetheless, other dimensions started to emerge, with each having a considerable impact in this industry. The construction community is currently witnessing a "shift from the 3D or visualization aspect of BIM to workflow-specific tools that are being directly applied to solve real-world problems, such as installation verification, sequencing and estimating" (Hardin and McCool 2015). However, the most used dimension is still 3D, with 4D and 5D closely after. Sustainability and FM, under the 6 and 7 dimensions, although fairly recent are expected to achieve the same importance as 4D and 5D in the following years. This is greatly attributed to the growing sustainability awareness and need to preserve existing buildings (Miragaia 2012, Rocha 2010). These last dimensions are implemented by emerging level 2 practitioners.

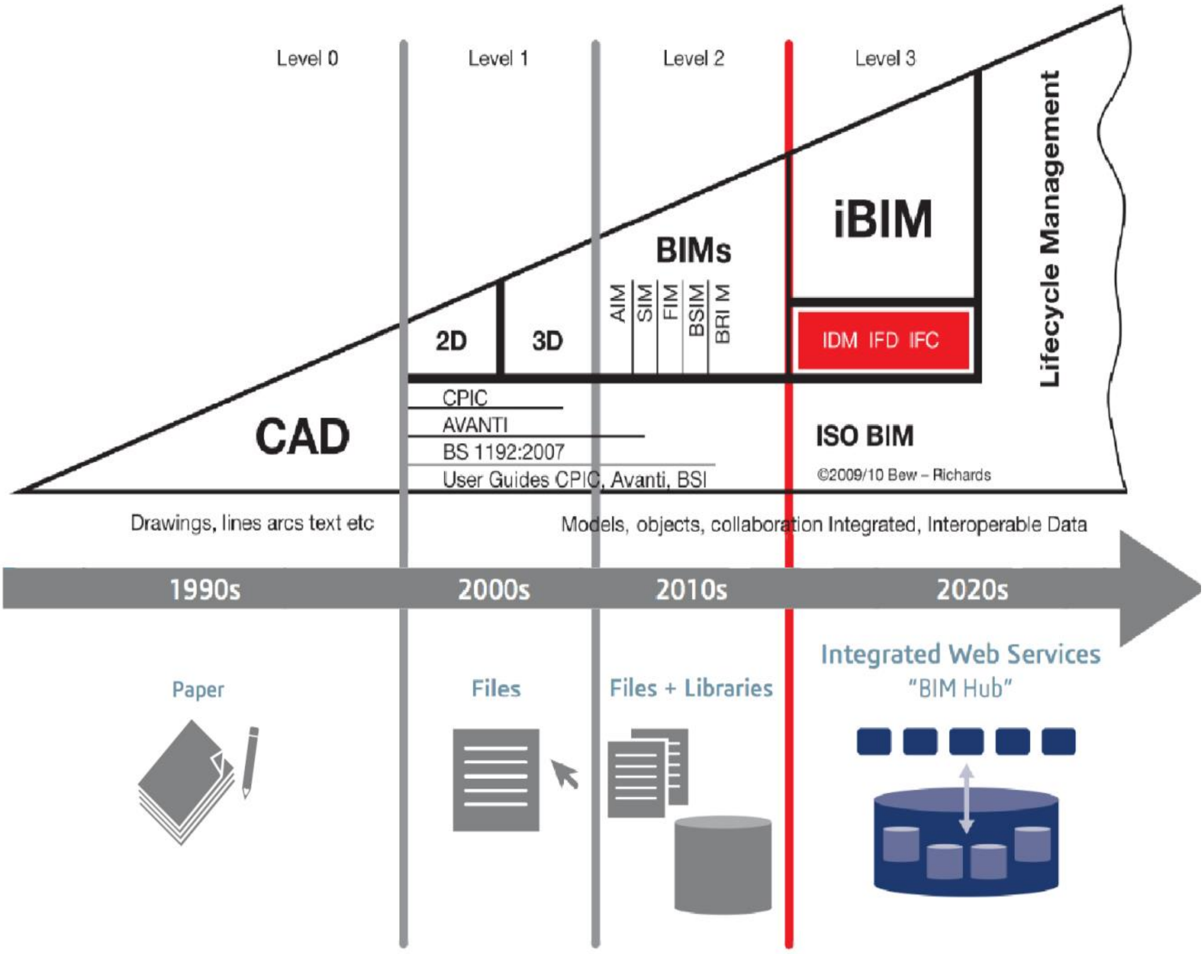

Fig. 3.2 – BIM maturity levels. Source: adapted from (Succar 2010)

3.2.7. Identifying the solution dimension

In the last few pages of this chapter it was possible to reference the extent of each BIM dimension, their history, particularities, and addressed topics. However, to properly close this section it is still necessary to indicate in which dimension the proposed software solution is located. As it was already mentioned in the first chapter, the designed software has the intent to offer an automated, fast and effortless stormwater runoff determination followed by the identification of the necessary solutions to diminish this runoff. This way, its main purpose is not only to aid in the achievement of greener building solutions but also to serve as a primary screening for possible LEED certification credits that rely solely over this topic. Since sustainability is the main focus of the proposed software it would be most logic to indicate 6D as this software dimension. However, as explained in 3.2.4., 6D is strongly connected with the others dimensions because of its broad concept being related to the economic, social and environmental aspects of construction. Thus, revising the solution capabilities, it is possible to identify the major impacts this software could achieve in managing stormwater runoff of existing buildings (7D), and the cost related data it could produce (5D). Furthermore, in order for this tool to work automatically, the model geometric characteristics are analyzed, hence also connecting 3D with the purposed program. As follows, this solution approaches not only the sixth dimension of BIM but also the third, fifth and seventh dimensions.

3.3. AUTODESK REVIT

“The parametric building modeling technology of Revit [...] has revitalized the architectural profession and brought the fun back into design. Those who have persevered in their learning and use of Revit have come to love the application and find it anathema to go back to traditional CAD. For them, the practice of architecture will never be the same again.” - Dr. Lachmi Khemlani (Khemlani 2004)

Autodesk Revit was specifically built to roof BIM features with the intent of helping architects, engineers, designers and contractors in the building industry. These features support and empower construction professionals to bring ideas from concept to reality with a coordinated and consistent model-based approach (Autodesk 2016b, Justi 2008). In the following section, it will be possible to observe a brief history of this software development, its purpose, core features and main strengths.

3.3.1. A BRIEF HISTORY OF REVIT

Parametric Technology Corporation (PTC) was founded in 1985, releasing the first version of Pro/ENGINEER in 1988. Pro/ENGINEER, a software for mechanical design, was the first major disruption in the CAD world, managing all design and analysis functions in the same database and data structure, using parametric modeling and offering an efficient design development system using a history tree. Basically, it offered most CAD tools in use until then and more while keeping a very high performance package. In the course of its fast growth, through the 1980s and early 1990s, PTC moved into most industries where computers were utilized for design and manufactures purposes. However, the AEC Industry was a hardest market even for PTC, and when PRO/Reflex was released the software didn’t have the expected acceptance resulting in the sale of Reflex to the US firm, Beck Construction in 1997 (Crotty 2013). However, in the same year, equipped with the knowledge of developing Pro/ENGINEER, Irwin Jungreis and Leonid Raiz split from PTC and launched their own software company called Charles River Software, later renamed Revit Technology Corporation, in 2000 (Quirk 2012). They had the intent of selling a parametric component-based system with a single-database and remarkable change propagation capabilities in the building industry. With this objective, Raiz and Jungreis gathered enough funding to hire architects and software developers to design Revit (name originated from the contraction of Revise-It) in C++ (Crotty 2013). In 1999 they hired Dave Lemont as CEO and in 2000 Revit was released. After its success, Autodesk bought Revit Technology Corporation in 2002, largely developing and improving the software and releasing the first version of Autodesk Revit in 2003 (BIMbuilder 2007).

Traditionally Revit was divided in three different programs:

- Revit Architecture – first released in 2003 under its former name Revit Building;
- Revit Structure – first released in 2005;
- Revit MEP – first released in 2006.

However, in 2013, Autodesk released Revit 2013 alongside Revit LT, a single platform that offered all the three previous software in one (Barbosa Monteiro 2013, Justi 2008). This way, the user can work in each project while inside the same software renting a license for the wanted products (Autodesk 2016b).

3.3.2. Revit's core features and main strengths

Since its debut, Revit revolutionized and propelled the BIM industry by providing a unique platform for visual programming through the creation of parametric families and allowing the time attribute to be associated with the building model (Barison and Santos 2010, Autodesk 2009, Quirk 2012). This offered the ability to design every component of a building in 3D, while still offering the necessary 2D drafts and letting the user retrieve any necessary information stored in the model for *n*D BIM related purposes. Also, since these parametric families established relationships between them, making any change in a Revit element would make that change propagate through the entire model, adjusting not only the 3D visual placement of elements but also its properties such as: area, perimeter, drawn sections, quantities, and so on. This concept, known as bi-directional associativity, was a distinguishing feature of Revit for many years and resulted on the creation of the term Parametric Building Model (Coenders 2008, Bhuskade 2015).

Revit also offers tools to manipulate the stored information on most phases of a building's lifecycle, since concept to construction and ultimately demolition (Barbosa Monteiro 2013). This is possible since Revit approaches a long list of specializations inside the construction industry sphere, which also makes Revit an incredible collaboration/work-sharing tool between diverse construction disciplines. This concept consist on the possibility of various users accessing the same project stored in a central station, which is updated each time an user finishes his part and synchronizes the local file with the stored project (Autodesk 2005).

In order to achieve a more realistic model of a building, Revit contains a simple but efficient rendering engine. This rendering can be accomplished by either configuring a raw "generic" material, choosing its texture, brightness, size, transparency, reflection, among other parameters or straightforward using Revit premade materials. These materials can be applied to every element inside Revit such as walls, roofs, floors, topography, columns, and so on (Demchak, Dzambazova, and Krygiel 2009). For a deeper experience there are also add-ins, plug-ins and cloud-based software that can be linked to Revit to better render the model.

Finally, the main strengths connected to Revit are (Khemlani 2004, Zolotova *et al.* 2015):

- Allowing an easier interoperability between 2D and 3D;
- A more immediate and accurate feedback for design decisions;
- A more simplistic and intuitive use when compared to other CAD and BIM applications;
- Automation of innumerous tasks such as 2D drawing, which in turn frees time for design;

- Bidirectional associativity of all views of the model;
- Compatibility with other products;
- Documents coordination and instant update of all documents, schedules, and views;
- Easy access to free and trial licensed versions, for a necessary evaluation of the software capabilities and its advantages for the company;
- Enabling better communication with clients and builders;
- Support offered by multiple user communities, actively communicating with each other.

3.4. AUTODESK DYNAMO

3.4.1. PEEKING UNDER REVIT'S INTERFACE

Autodesk Dynamo is an open source software, released in 2011, strongly influenced by VPLs such as Grasshopper 3D for Rhinoceros 3D (Ferreira and Leitão 2015). Its purpose is not only to create graphical representations of complex geometries but also efficiently and automatically manage the information flows between Revit and cloud services or a specific database (Mahdjoubi, Brebbia, and Laing 2015). This gives users the flexibility to efficiently create tools for Revit without relying on programmers to create the needed plugins (Wong 2015). However, as it will be possible to understand later in this section, Dynamo can work without a Revit connection, despite its main purpose being to enhance the workflow of Revit as a plugin, building a pathway into its underlying core (McGinley and Fong 2015).

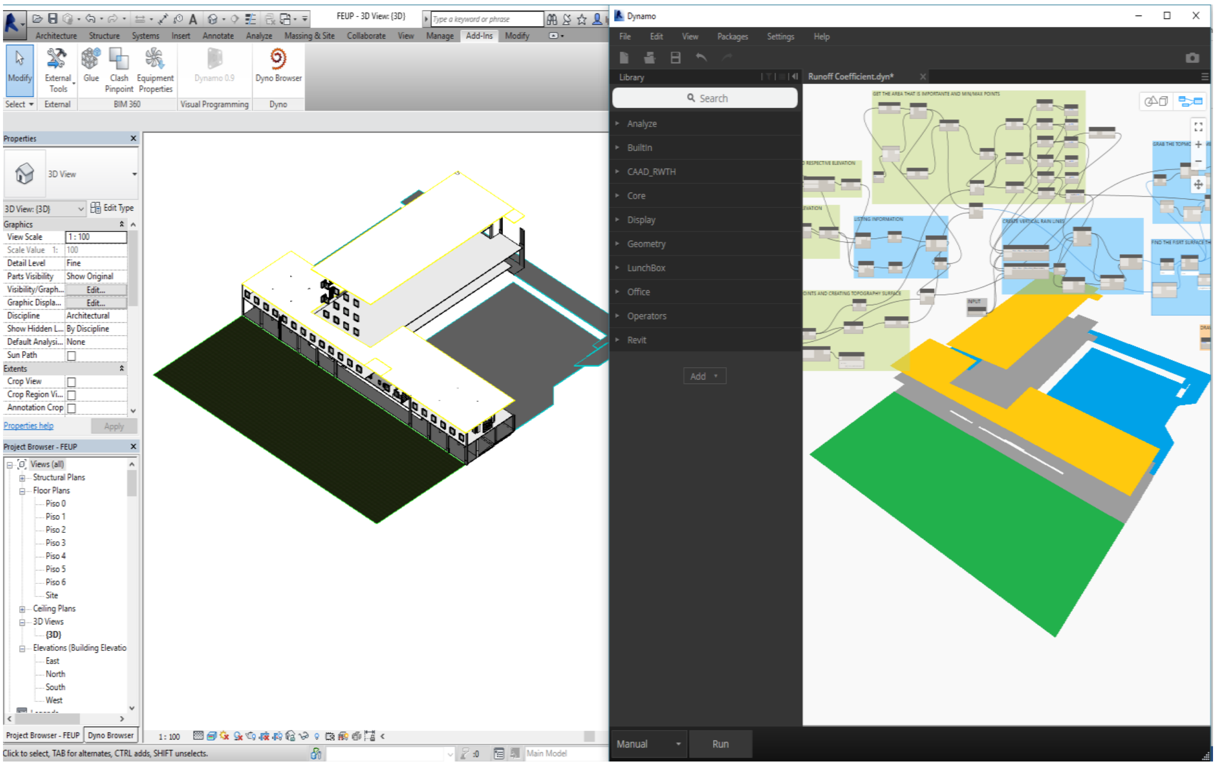

Fig. 3.3 – The software prototype in development, showing Revit and Dynamo side by side

Being a VPL, Dynamo offers Revit users from AEC Industry a way to explore in-depth parametric design and extend BIM capabilities without having to understand a typical programming language (Li

2015). Instead of the usual code lines, in Dynamo, just as Grasshopper, the user is presented with pre-packaged “nodes”: graphical algorithms to be used inside a logic environment (Autodesk 2015). Each node has a purpose, a functionality. By dragging and dropping these nodes inside the canvas interface, and linking it to other nodes through connection wires, it is possible to create a logical workflow. These wires connect to the different nodes through input and output ports (respectively on the left and right side of the node) which, as the name suggests, are used to introduce and extract information from nodes if the correct connections are made. This means that input and output ports from different nodes must have compatible types of information in order to achieve a successful connection.

Nodes can vary tremendously in purpose, ranging from the creation of simple numbers and text to the creation of complex geometries, mathematical functions and parametric overrides inside Revit. Finally, Dynamo also supports the use of “code blocks”, which provide the ability to write small scripts in Python, allowing a more advanced user an even deeper customization that might not be achievable through the use of regular nodes (Dynamo 2015, Ferreira and Leitão 2015). In Figure 3.4 it is possible to understand the behavior of these nodes through a simple multiplication of a number sequence for a single number, by first creating the sequence.

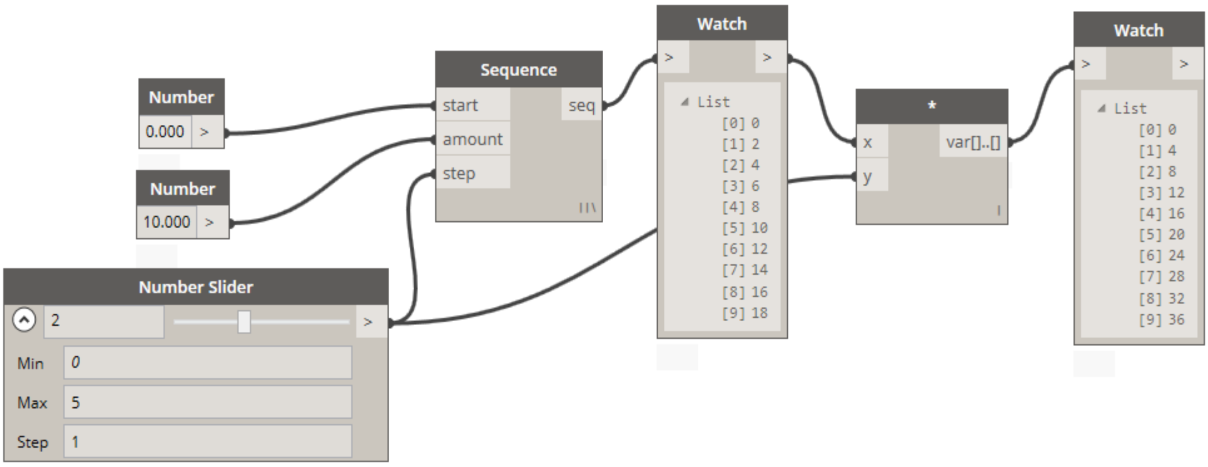

Fig. 3.4 – An example of how Dynamo nodes work and its applications

3.4.2. “Grasshopper for Revit”

Since its debut, Dynamo has been addressed as “Grasshopper for Revit” given that both plugins allow users to develop their own design tools through a VPL. However, Dynamo is largely considered to be a more limited version of Grasshopper since the former’s free forming capabilities lack when compared to the latter. Yet, this comparison is extremely superficial, concealing the deeper differences between the two software. Rhino’s strength comes from its complex geometries and thus Grasshopper offers extensive tools for form-making in order to achieve these goals. On the other hand, Revit excels at building management, easily controlling all types of information inside a building. As such, Dynamo seems better equipped to add value to data manipulation (Autodesk 2015). Comparing Dynamo free forming geometries capabilities to Grasshopper is as irrelevant as comparing Grasshopper information management to Dynamo (Wong 2015). Overall, in both software, visual scripting allows designers to achieve a greater control over the design information while also providing a mechanism for parametric form generation (Gregorius and Tony 2015).

3.4.3. Dynamo, Dynamo Sandbox and Dynamo Studio

Dynamo is commercialized in three different packages: “Dynamo”, “Dynamo Sandbox” and “Dynamo Studio”. Each of these packages is very similar to the others with only a very specific detail changing, its connection with Revit and cloud services. The first version, “Dynamo”, runs as an add-in for Revit. This means it has access to the Revit model, Revit Application Programming Interface (API), Revit related nodes and uses the Revit’s authentication and license for cloud services. “Dynamo Sandbox” is the free Dynamo core technology, with access to scripting language, node diagramming and execution design. Yet, despite having some of the available Revit nodes it does not have access to cloud services, since the connection between the two software does not exist. Finally, “Dynamo Studio” is a visual programming platform that functions fully independently of any other application. It has access to all the Autodesk’s geometry tools and cloud services (similarly to “Dynamo”) but does not require the user to buy a Revit license (Kron 2015).

3.4.4. Pros and Cons

As seen in the last few pages, Dynamo offers significant advantages for designers who want to explore Revit’s full potential through data management and geometry creation. However, possible the most advantageous aspect of Dynamo is yet to be mentioned.

In Dynamo forms are created based on flexible numerical parameters rather than single pre-determined values. This enables the possibility to explore design alternatives by changing this numerical parameters even in the early stages of design (Gregorius and Tony 2015). In the latest versions of Dynamo, it is even possible to create and save a large number of presets for these parametrical variables, to keep any amount of design option inside a simple folder. This way, instead of wasting huge amounts of time modeling different aspects of our building in order to perceive if it is a good option to consider, by changing a few variables, in a matter of minutes the user can create hundreds of alternatives to the main design (Williams 2015).

Obviously, Dynamo, as a programming software, also has some disadvantages. The major one is normally considered to be the need to associate Dynamo with Revit. This means the programs created are not portable and need both software installed in a computer to run any custom tool created. However, as seen by Dynamo Studio, this aspect is being focused by Autodesk. Another disadvantage is the programming language used. VPLs, despite being easy to learn, do not scale well with the program complexity. Textual Programming Languages, despite introducing a barrier for newcomers, are much more flexible. Although this aspect is also, in some extent, solved by the use of “codes blocks” and Python, since Python is a very simple language, normally used to teach beginners how to program, it also does not cover the full extent of VPL’s barriers (Ferreira and Leitão 2015).

Finally, Dynamo was chosen to be implemented in the creation of the purposed software by a number of reasons, including its native relationship with Revit, its ability to represent the Revit model as a 3D geometry inside the VPL canvas interface and its community support. Although difficulties were predicted after initially investigating Revit’s API, since VPLs are rising in popularity and the author already had a good knowledge over the more traditional programming languages, the challenge to use Dynamo was accepted as a way to not only amplify the knowledge about programming but also give a significant contribution to Dynamo and its growing community.

3.5. DYNO

In the previous section of this chapter, Dynamo was introduced as the VPL used to create the inner structure of the proposed software. However, as of the moment of this thesis, Revit does not provide any Software Development Toolkit (SDK) for Dynamo and its API is highly .NET oriented in order to support the new "web services" stored in the Cloud (Autodesk 2016a). As such, Revit has well established features helping third party applications using C#, C++ and Visual Basic, but lacks support for others languages like Dynamo (Dynamo 2016). This way, the possibility to develop an application for an end user using Dynamo was highly doubtful. In this section, Dyno will be presented, a recent software developed by Alexey Lobanov for "organizing, deploying and running Dynamo workspaces for Autodesk Revit" (Lobanov 2016a).

In its core, Dyno intends to extend Revit possibilities alongside Dynamo, allowing the common Revit user to apply Dynamo proficiently through the creation of an interface inside Revit and the automation of Dynamo workspaces. This way, Dyno addresses the lack of interactivity between a Dynamo programmer and the end user, which many classify as the main issue surrounding Dynamo (Dynamo 2016).

Dyno performs as an add-in inside Revit, only working if Revit 2015 or 2016 are installed. It is a small application meaning it is of simple use and quick installation. Furthermore it is intuitive, which contributes to easily learn how to create presets, buttons and connections to Dynamo nodes.

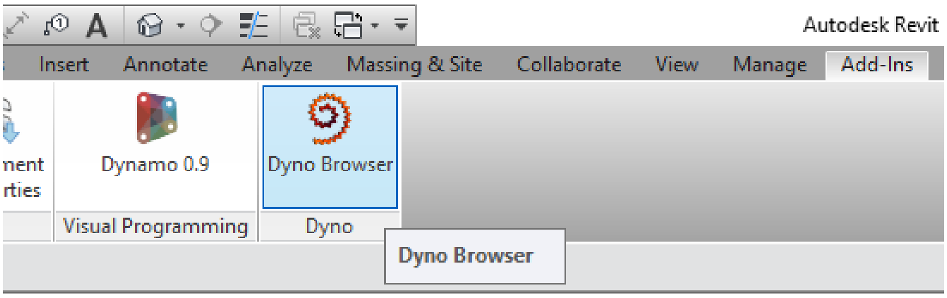

Fig. 3.5 – Dyno's library, Dyno Browser, inside the add-ins tab in Revit

As seen in the last paragraph Dyno connects to Dynamo nodes in order to import and export information from Dynamo workspaces. To do so, Dyno uses presets, a set of .dpr extension files used to create the desired interface through Dyno Browser (Dyno's library inside Revit). Each preset file is individually made for each Dynamo workspace and must have the same file name. Hence Dyno can connect to a handful of input nodes inside Dynamo such as "number", "integer slider", "double slider", "string", "boolean", "select", "file path", and "directory path". Any of these nodes can be programmed to display a default input, list specific inputs to be selected or simply allow the user to write the input information. Also, to shorten the task of deploying and running Dyno Browser, Dyno can create tabs and buttons to be displayed on the Revit tool ribbon, allowing for an easy launch of the Dynamo workspace. These buttons are created using a simple .txt file inside Dyno folder.

To create the needed presets and buttons files, the user can employ C# and create these files using a source code editor (i.e. Notepad++) or, in alternative, he can also use the node package *Dynablaster*, inside Dynamo, which contains a set of intuitive nodes for generating Dyno presets (Lobanov 2016b).

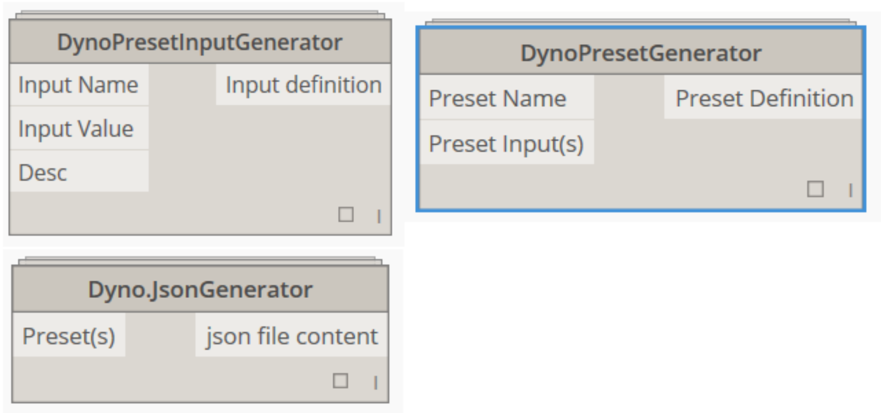

Fig. 3.6 – *Dynablaster* package containing Dyno presets generating nodes.
Source: adapted from (Lobanov 2016b)

Finally, Dyno currently entered beta testing and, although it still provides a reliable interface and automation for Dynamo files, there are plenty of small bugs to endure and work around (as expected from a recently alpha software). Also, since Dyno is still in development there is a considerable lack of detailed information available to the general public and, as such, it should be pointed out that most information shown in this section was obtained contacting the sole developer of this software, Mr. Lobanov himself.

4

STORMWATER RUNOFF

4.1. THE PROPOSED SOFTWARE

As it was briefly mentioned through this work, the main objective of this thesis is to contribute in connecting BIM and Sustainability by means of an automated software. In this section, the central objectives surrounding this software will be introduced, preparing the grounds for the remaining thesis where the program will be thoroughly dismantled piece by piece in order to explain each and every step needed to complete the purposed objectives. As follows, the design software, entitled "StormWater Runoff", has two main objectives:

- Automatically determine the rainfall runoff of any building site;
- Correct the previously determined runoff by automatically proposing the implantation of LID-BMP.

In order to achieve these goals, a set of BIM tools, already mentioned in previous topics, were used: Revit, Dynamo and Dyno. Figure 4.1 illustrates an initial concept on how these tools were implemented in the design of the software and how they interact between themselves.

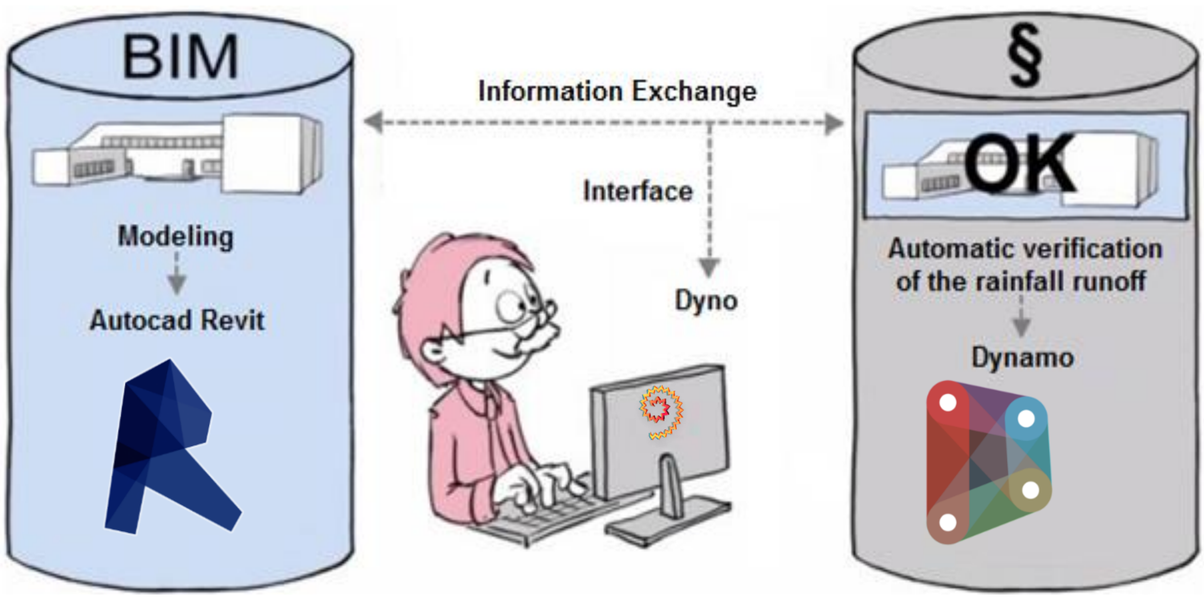

Fig. 4.1 – StormWater Runoff workflow architecture composed by Revit, Dynamo and Dyno.
Source: adapted from (Moço 2015)

This software involves all Sustainability topics mentioned and discussed so far. It bases its existence upon some of the sustainable frameworks principles while using the LEED certification system and the runoff Rational Calculation method to create a proper and concise objective while also offering the means of achieving it. It will also require the BIM knowledge previously explored in order to not only conceive the actual code for the software but also create the interface for the end user. This end user is mainly represented as a professional related to the AEC Industry, such as an architect, engineer, contractor, building owner, manager, among others; however it can also be used by a common individual without any previous AEC knowledge, such as a concerned citizen or a sustainability pursuer trying to achieve LEED certification. As it was explained before in section 2.5, this green certification system suggests the hiring of LEED accredited professionals to pinpoint which credits should be pursued, as well as proposing the use of its manuals and guides as a complementary tool. The cost of this task alone can rise above 10000€ depending on the certification level, project size and schedule deadlines (USGBC 2016a). By introducing a minimum amount of information inside this software, users can distinguish between pursuable and non-pursuable runoff related credits, considerably reducing this cost. As such, this software has been developed to behave as an expert system, providing specific AEC knowledge to the end user through a simple graphical user interface (GUI). Thus, most of the language applied is user friendly, focusing in achieving a simple, lean and intuitive interface, while creating a natural workflow for the software. However, although measures are taken to address the common user, it is also possible to override most inputs, in order to achieve a runoff with greater precision. This aspect of the program is intended for more knowledgeable users who pretend to use this software as an accurate tool for measuring the rainfall runoff. This way, as a final objective behind these software goals, this program will enable the user to gather all the necessary information to retrieve any of the 61 rainfall quantity related LEED credits, distributed by the various LEED building categories in LEED V4. Moreover, since it is still possible to acquire credits for LEED V3, this software also allows the user to achieve all of the 20 credits related to rainfall runoff in this version. The completed list of all possible obtainable credits through the use of the proposed software can be seen in Tables 4.1 and 4.2.

Table 4.1 – LEED V3 Credits (USGBC 2016b)

<table>
<tr><th colspan="3">LEED V3</th></tr>
<tr><th>CATEGORY</th><th>CREDIT NAME</th><th>AMOUNT</th></tr>
<tr><td>LEED ND: Plan</td><td rowspan="2">Stormwater Management (GIBc8)</td><td rowspan="2">4 credits</td></tr>
<tr><td>LEED ND: Built Project</td></tr>
<tr><td rowspan="2">LEED O+M: Existing Buildings</td><td>Stormwater Quantity Control (SSc6)</td><td>1 credit</td></tr>
<tr><td>Rainwater management (SSpc16)</td><td>1 credit</td></tr>
<tr><td>LEED BD+C: New Construction</td><td rowspan="5">Stormwater Design: Quantity Control (SSc6.1)

Stormwater Design: Quality Control (SSc6.2)</td><td rowspan="5">1 credit each</td></tr>
<tr><td>LEED BD+C: Retail</td></tr>
<tr><td>LEED BD+C: Core and Shell</td></tr>
<tr><td>LEED BD+C: Schools</td></tr>
<tr><td>LEED BD+C: Healthcare</td></tr>
<tr><td></td><td>TOTAL</td><td>20 credits</td></tr>
</table>

Table 4.2 – LEED V4 Credits (USGBC 2016b)

<table>
<tr><th colspan="3">LEED V4</th></tr>
<tr><th>CATEGORY</th><th>CREDIT NAME</th><th>AMOUNT</th></tr>
<tr><td>LEED ND: Plan</td><td rowspan="2">Stormwater Management</td><td rowspan="2">4 credits</td></tr>
<tr><td>LEED ND: Built Project</td></tr>
<tr><td>LEED BD+C: New Construction</td><td rowspan="10">Rainwater Management</td><td rowspan="10">3 credits</td></tr>
<tr><td>LEED BD+C: Core andShell</td></tr>
<tr><td>LEED BD+C: Schools</td></tr>
<tr><td>LEED BD+C: Retail</td></tr>
<tr><td>LEED BD+C: Healthcare</td></tr>
<tr><td>LEED BD+C: Data Centers</td></tr>
<tr><td>LEED BD+C: Hospitality</td></tr>
<tr><td>LEED BD+C: Warehouses and Distribution Centers</td></tr>
<tr><td>LEED BD+C: Homes</td></tr>
<tr><td>LEED BD+C: Multifamily Midrise</td></tr>
<tr><td>LEED ID+C: Commercial Interiors</td><td rowspan="3">Innovation: Rainwater Management</td><td rowspan="3">1 credit</td></tr>
<tr><td>LEED ID+C: Retail</td></tr>
<tr><td>LEED ID+C: Hospitality</td></tr>
<tr><td>LEED O+M: Schools</td><td rowspan="7">Rainwater Management</td><td>2 credits</td></tr>
<tr><td>LEED O+M: Existing Buildings</td><td rowspan="6">3 credits</td></tr>
<tr><td>LEED O+M: Retail</td></tr>
<tr><td>LEED O+M: Data Centers</td></tr>
<tr><td>LEED O+M: Hospitality</td></tr>
<tr><td>LEED O+M: Warehouses and Distribution Centers</td></tr>
<tr><td>LEED O+M: Multifamily</td></tr>
<tr><td></td><td>TOTAL</td><td>62 credits</td></tr>
</table>

This software can also be used to justify design decisions for the building, being able to be useful not only in the design phase but also in the construction and maintenance phases, for example, in case of unexpected issues or the need to correct the runoff value post construction.

Finally, it should be addressed that few inputs have to be introduced for the software to work. These inputs are limited to some rainfall related variables, the building use (in order to obtain the initial runoff value), and a few design and cost driven choices. These last few inputs are required to achieve a priority order between the various infrastructure alternatives in the actual correction of the rainfall runoff. Figures 4.2 and 4.3 show the logo and icon created for the software, which will be displayed inside Revit.

Fig. 4.2 – StormWater Runoff logo

Fig. 4.3 – StormWater Runoff icon

4.2. REVIT CATEGORIES

To better realize how the created software works, it is necessary to first understand how Revit processes the model information, particularly its Categories, which are used by the StormWater Runoff software. This section will fulfil this purpose, introducing Revit's parametric hierarchy.

Revit's hierarchy has three levels: Categories, Families, and Types. Every element in Revit is considered a Family, and each Family belongs to a Category. Furthermore, there can be various variations of each element, originating the different Types. As an example, a concrete slab and a structural wooden floor are both from the same Category (Floor) but from different Families. Also, a 125 mm and a 150 mm thick concrete slab share the same Family, however, display different Types.

In Revit, every element answers to this hierarchy, creating a simple and easily understandable workflow, greatly influenced by usual AEC Industry organizations, while setting a system capable of managing relationships between classes of elements as well as graphical representation for each class.

At the core of this organization is a fixed list of Categories to which all elements belong. This list cannot be altered, meaning new Categories cannot be created, and neither can the existing ones be eliminated or renamed. Although this may seem strict, it helps the user maintain a consistent graphical representation across his projects. There are two types of categories:

- Model Categories – which include the typical elements such as roofs, floors, topography, walls, furniture, along with other categories related to architectural projects;
- Annotation Categories – which include all the annotations, symbols, and descriptive data added to the building. Examples include dimensions, tags, and text notes.

Lastly, within each Category it is possible to find multiple Subcategories. These let the user modify graphics with increased precision, turning the concept of Categories even more powerful and natural to workflows.

4.3. PREREQUISITES FOR REVIT MODEL

As already mentioned throughout this thesis, the most effective way of achieving a sustainable project is to consider and incorporate sustainability issues at a stage even before a design is conceptualized. This is the same as saying that for a sustainability software to be most impactful and useful as a design tool, it should be introduced as early as possible in the project to allow for an early collaboration between the design and assessment teams. As such, a pivotal concept considered throughout the software development was the Level of Development (LOD) for the Revit model.

The LOD specification is a reference system that enables BIM practitioners in the AEC Industry to indicate and articulate, with a high level of clarity, the content and reliability of BIM models for various stages of the design and construction process. It easily defines and illustrates characteristics of model elements for different building systems, allowing for model authors to define what their models can be relied on for, at the same time that users clearly understand the usability and limitations of the received models. In this specific case LOD is used to alert the user of the necessary Revit model requisites in order to be run by the StormWater Runoff software (Forum 2015).

LOD is typically divided in 5 levels, LOD 100, LOD 200, LOD 300, LOD 400, and LOD 500, with each level requiring more information than the previous level. An extra level is commonly included between the third and fourth levels – the LOD 350 (AIA 2013):

- LOD 100 – "The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements";
- LOD 200 – "The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element";
- LOD 300 – "The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element";
- LOD 350 – "The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element";
- LOD 400 – "The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element";
- LOD 500 – "The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements".

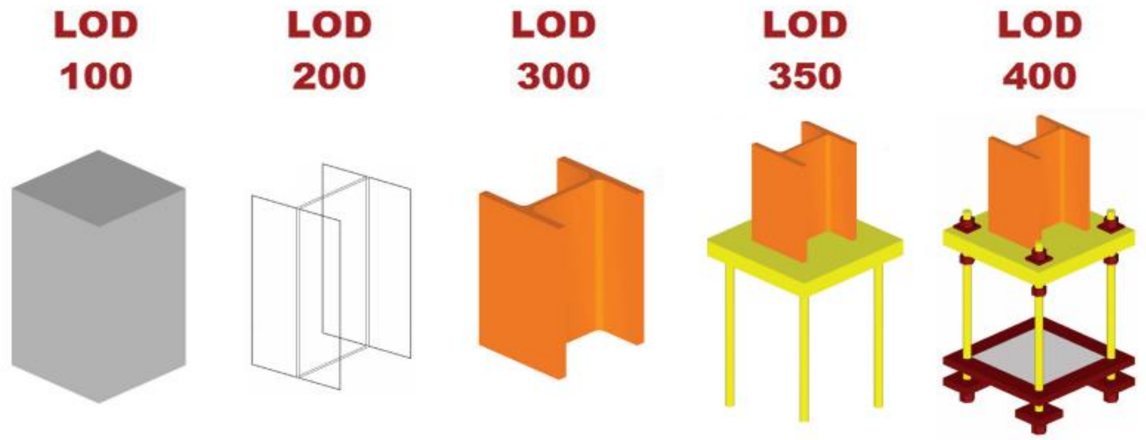

Fig. 4.4 – LOD levels. Source: adapted from (Forum 2015)

This way, since the designed software may be used in the earliest stages of the project, a low LOD should be required. As such, the proposed software manages to accomplish its goals by only requiring the horizontal areas linked with the building in study. However, a fundamental key for the correct performance of the software is the adequate categorization of the elements corresponding to these areas. In fact, all the obtained areas must correspond to an element inside one of these Categories: Roofs, Floors, and Topography. Obviously, each of these Categories must be correctly filled in (i.e. floors slabs on the first Floor cannot be categorized as Roofs or Topography).

This means the BIM model used alongside the software is required to at least display a LOD 200 specification or, if possible, a LOD 300 specification for better accuracy connected to the software results. It should be stressed that the low prerequisites also contribute to the pursued software simplicity, relieving the user of complicated modeling burdens or requiring financial investment to obtain unnecessarily complex Revit models.

4.4. SOFTWARE ARCHITECTURE AND OVERVIEW

In this section, a functional overview of the software functions will be presented. However, it should be noted that this is not a complete walkthrough of the actual software code (which is present in Attachment A) but instead a high-level summary of how the StormWater Runoff software works or, in other words, its architecture. As such, for a better understanding of the written overview, in Figure 4.5 the reader can comprehend the software architecture by means of its flow chart.

The software start when the user opens Dyno inside Revit. There the user is faced with two tabs: the “Initial Runoff” and the “LIDBMP”. Together, both create the entire designed software. Starting with the first tab, the “Initial Runoff”, the user finds an assembly of required inputs. All these inputs will be thoroughly explained in sections 4.5 and 5.3.2. However, special attention has to be given to the “override” inputs since, as it will be possible to understand in Attachment A, these inputs have quite an impact in the way the software works. In fact, to obtain the initial runoff the software has to extract information from the Revit model and the designed databases, using a fair amount of computing to do so. Yet, if the user decides to override the preset values, the software does not require the database information, excluding the necessity for the software to link with the created databases.

Nevertheless, with or without the values overridden, if all the inputs are correctly filled, the first half of the software acquires the initial runoff volume by computing equation 2.1 and 2.2 inside Dynamo.

After acquiring the initial runoff, and other information also retrieved from the first half of the software, the user may continue to the second tab inside Dyno: the “LIDBMP”. This second half of the software computes the LID-BMP introduced in section 2.6.3. to achieve a determined LEED credit or a desired final runoff volume. As such, alongside the required inputs for the second half of the program, Dyno asks the user if he is pursueing a LEED credit or a desired final runoff for the building site. Depending on the answer, the software calculates the necessary runoff to be mitigated by applying the LEED requirements or by subtrating the desired final runoff with the initial one, obtained from the first tab.

Acquired the necessary runoff to be eliminated, the software goes on calculating multiple LID-BMP solutions to achieve the desired final runoff. Obviously, this calculations will depend on the rest of the introduced inputs to decide which LID-BMP or which combination of LID-BMP is best suited to achieve the user’s objectives. After obtaining the best option, the software displays to the user the required LID-BMP, the occupied area and the individual costs.

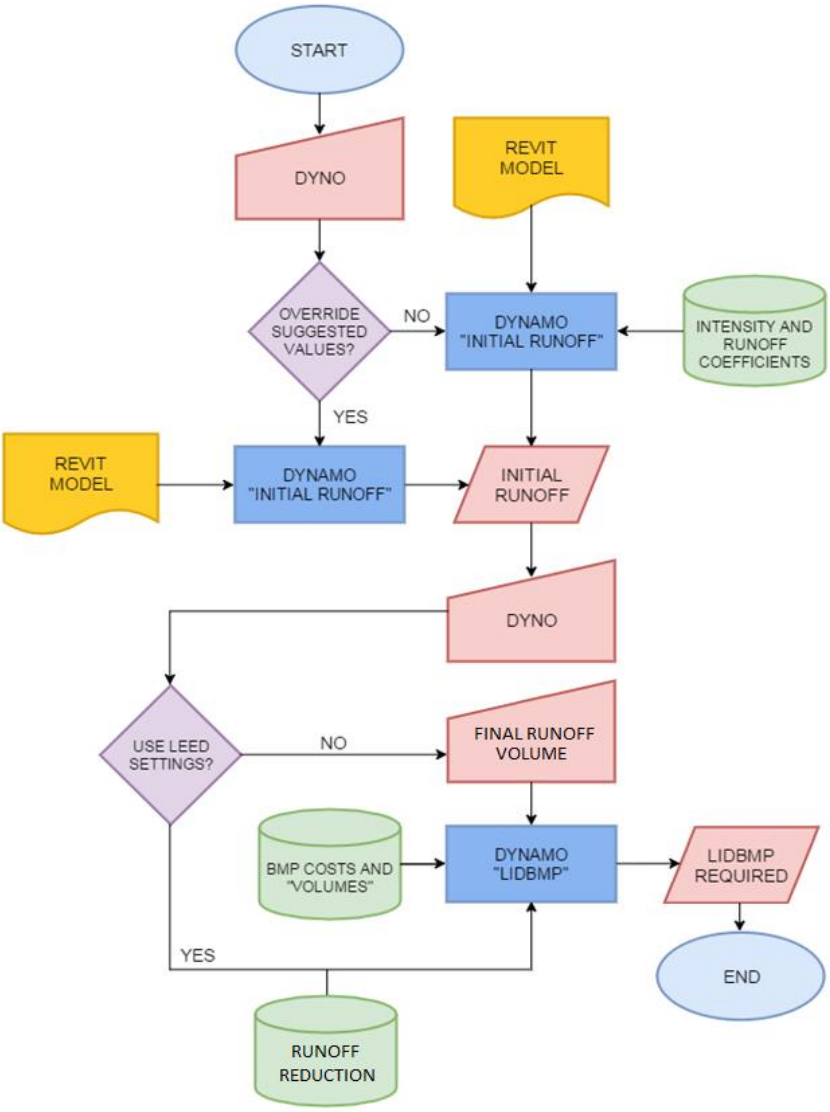

Fig. 4.5 – StormWater Runoff software architecture

4.5. DYNO CODE

As seen throughout this chapter, there are a series of simple inputs needed to be introduced in Dynamo in order for the software to properly work. Some of these inputs are directly obtained from the Revit model but most have to be manually introduced through Dyno. In Attachment A, as well as the last section, it is possible to understand how the input values are managed by Dynamo, however, no details are shown regarding the actual introduction of information. As such, in this section, the procedure to create the software interface is presented and explained, thus completing the full analysis of the StormWater Runoff software.

As seen in 3.5, for Dynamo to work properly, two different types of files must be created: the preset files with the .dpr extension and the button files with a simple .txt extension. To correctly run the software two preset files and one button file were created. Also, the preset files had to be created with the exact same name as the Dynamo files in order to create a virtual link between them. As such, the first one, which obtains the necessary information to calculate the rainfall runoff, was named "Initial Runoff.dpr" and, the second one, in charge of retrieving the necessary input to determine the required LID-BMP, was named "LIDBMP.dpr".

By analyzing these .dpr files in Attachment B, it is possible to conclude that both files start with a "hideOriginal" tag. This is done to clean up the software interface. Then, comes the actual "presets" which create the ways to actually introduce inputs. In both files we can encounter three alternative controls: text boxes, drop boxes and boolean boxes. Text boxes are the easiest to identify. They are created by introducing the input name between quotation marks, followed by the preset value which, in this software case, is typically "0.00". Next, the drop boxes are typically the largest lines of code. They also start with the input name between quotation marks, but they must also contain a "value", which works as the preset, followed by an indefinite number of other "values", which populate the drop box. Finally, booleans are also easily identifiable since they possess a "value" containing a "true" or "false" input. The resulting interface from both these .dpr files, which can be found in Attachment B, can be seen in Figure 4.6, and 4.7.

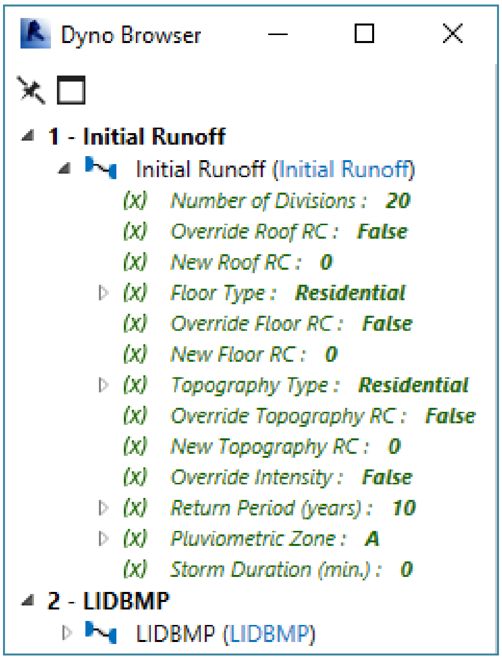

Fig. 4.6 – Dyno interface obtained from the Initial Runoff.dpr file

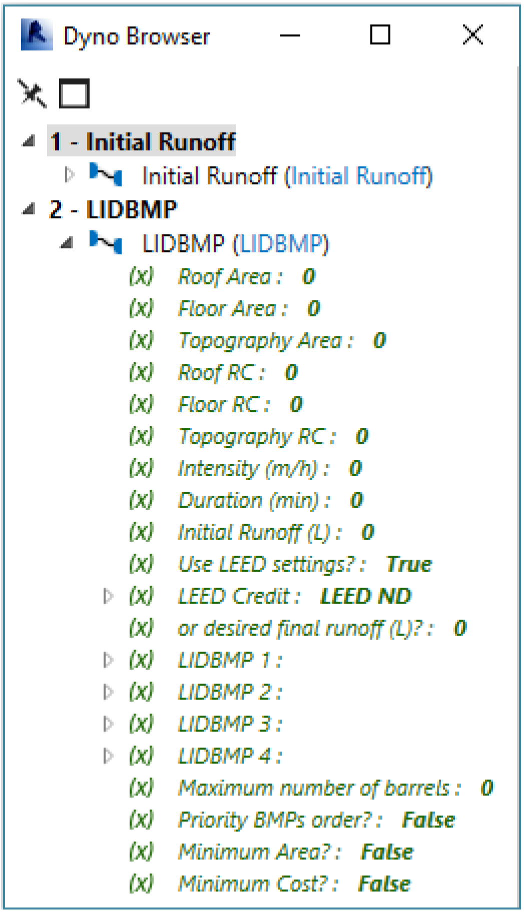

Fig. 4.7 – Dyno interface obtained from the LIDBMP.dpr file

Lastly, the buttons file, named “buttons.txt”, has only one line of code and can be seen in Figure 4.8:

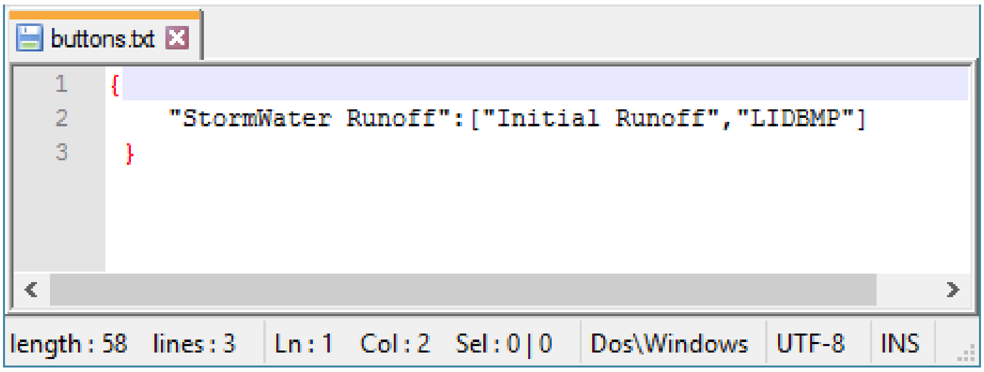

Fig. 4.8 – Code for creating the software tab and buttons inside Revit

This file basically creates a tab in Revit’s tool ribbon entitled “StormWater Runoff”, which contains two buttons named “Initial Runoff” and “LIDBMP”. The button’s design can then be set to default, which creates buttons with the name initials and different colors depending on the ribbon they are on, or can be overridden inside Revit's properties to upload the desired .ico image. These buttons and ribbon can be seen in Figure 4.9.

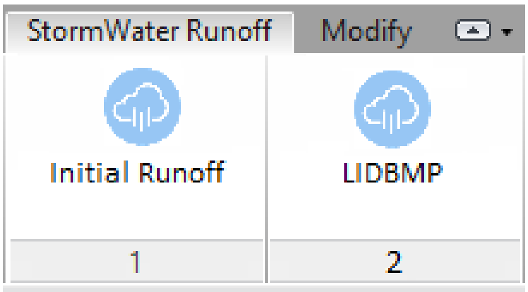

Fig. 4.9 – Created tab and buttons inside Revit

5
CASE STUDY

5.1. CASE DESCRIPTION

Within the scope of this thesis, the development of a case study is mandatory to allow for a better understanding of the designed software capabilities and restrictions. In this context, this case study focuses on the creation of the parametric model used alongside the Stormwater Runoff software, the actual running of the software and, finally, the acquirement and analysis of the results. This way, the following chapter aims to help illustrate the actual usefulness of the created software inside the AEC Industry.

The guiding principles of the case study are, on one hand, to validate the possibilities of parametric modeling and VPL while producing a precise rainwater runoff for the building site and, on the other, generate correct environmental driven solutions that enable the proper management of this runoff. Thus, this case study strongly resembles the actual application of the designed software to a real practical situation inside an AEC company.

The designated project is based upon the Civil Engineering Department building of FEUP (blue striped area visible in Figure 5.1, also seen in Figure 5.2), located in Porto, Portugal. Currently this faculty enjoys a campus with about 100000 square meters, with its facilities consisting of a series of buildings along two main axes, which converge on the west side of the campus. This converging point is located in the main lobby which, along with the Library on the opposite far side of the faculty, limit the campus dimensions. The first axis, on the southern side of the faculty, contains the main buildings which are composed by auditoriums and classrooms. The second axis, to the north of the previous main buildings, is composed of a series of Departments, one for each of the major faculty courses.

The BIM model that will be used in this case study has been developed collaboratively by several students in recent years (Rodas 2015, Barbosa Monteiro 2013) and, although not a complete replica of the actual building, this model closely matches the real building, apart from the Building Division's Laboratory (red striped area in Figure 5.2). This is because the modeling of the laboratory is yet to be finished, thus excluding it from the model used in this case study. However, it should be pointed that although this portion of the building was eliminated from the present model, the author contributed to aspects of the model such as floor creation, correction of measurements, proper establishment of categories and building material, and pavement-wall connections.

Fig. 5.1 – FEUP

As shown in Figure 5.2 and 5.3, the model consists of an approximately "T" shaped building, surrounded by a sizable lawn to its south, a street to the north and two parking lots on its eastern and western sides. The building can be roughly divided in two bodies. The first, parallel to the lawn, has no ground floor, having its only floor on the first level supported by the second body and a large amount of columns. This section mainly contains Professor's and administration related offices. The second body has five floors, including the ground one, and majorly contains Professor's offices. Both bodies display a seemingly rectangular shape, with flat roofs and completely vertical walls. Also, the parking lots and the walkway behind the building are built with cobble stone and connect to the road in the back of the building through two different ramps.

The actual modeling was done through the Autodesk Revit 2016 software, while also resorting to Dynamo to finalize minor measurement details.

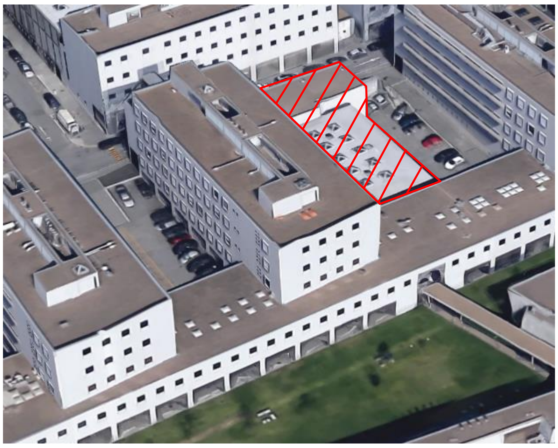

Fig. 5.2 – Civil Engineering Department

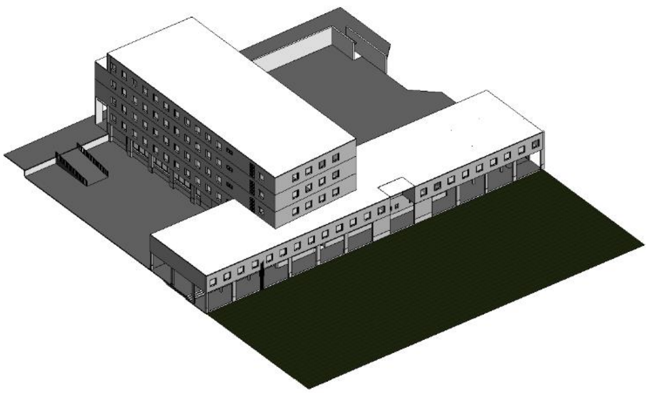

Fig. 5.3 – Revit parametric model

5.2. BUILDING MODEL

As previously said, the current model has been built by various students along the last few years. As such, to bring clarity to the model and better perceive which aspects of the building have already been modeled, in Figure 5.2 and 5.3, both the real building and the parametric model can be seen side by side. This way, it is possible to clearly see the lack of three main parts of the building. The major one, previously stated, is the laboratory, which is not modeled at all. The second, is the infrastructure present on the roofs which are not easily accessed by students. The third and last part is the covered walkway connecting this Department to the main classrooms building.

Excluding these three parts, the remnant model is extremely accurate both on measurement and modeling materials although its LOD is not particularly high. From the outside, the walkways and parking lots were modeled with cobble stone while the lawn was modelled with grass. The roofs, columns and walls generic materials were modified to include the necessary finishes and even examples of steel reinforcements were created to simulate the existing one. The windows, doors and outdoor stairs are also correctly modeled. From the inside, all divisions were created with the proper measurements, while also giving attention to the indoor stairs, the general and emergency doors, and even the furniture: chairs, tables, bookshelves, etc. Despite this, the inside modeling materials are more generic, as is typical of lower LOD models, with the application of the “basic wall” and “basic floor” materials from the Revit library.

However, as seen in chapter 4 and Attachment A, for the designed software to work properly, the only parametric elements that really need to be correctly modeled are the Topography, the Roofs, and the outside Floors, since these are the elements that contribute to the rainfall runoff. As such, using Revit properties, it was possible to manually count 1 Topography, 5 Roofs and 24 Floors (Figure 5.4). The large amount of floors comes from the outside stairs being somewhat incorrectly categorized as floors.

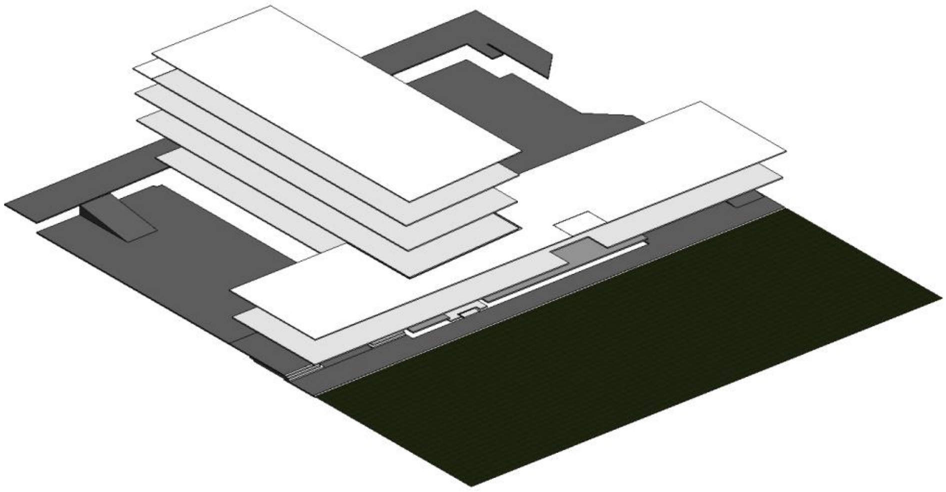

Fig. 5.4 – Topography, Roofs and Floors in Revit model

Finally, by also manually retrieving each of these elements areas and summing them, it was possible to conclude that there are approximately 2115 square meters of Topography, 1883 square meters of Roofs and 8213 square meters of Floors. All the presented values are summarized in Figure 5.5 and will be used as validation for some of the software results.

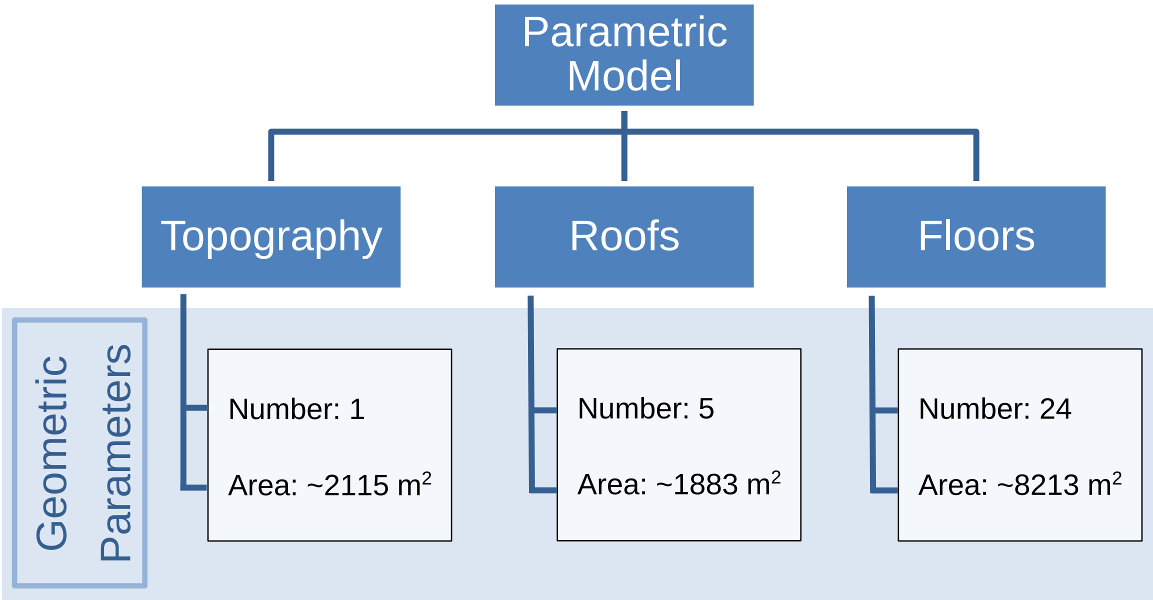

Fig. 5.5 – Geometric Parameters

5.3. Problem formulation and Dyno inputs

As stated throughout this thesis, the designed software can be used with different intents. Furthermore, the program needs a few inputs to be introduced through Dyno. In this section, the objectives for this case study are outlined and the reasoning behind the chosen initial conditions or inputs for the calculation of the initial rainwater runoff and LID-BMP selection is explained.

5.3.1. Problem Formulation

The software capabilities are employed with the purpose of achieving the following objectives:

a) Obtain the current rainwater runoff created in the Civil Engineering Department vicinity with sufficient accuracy to use the second half of the program correctly;
b) Run the software twice, once to pursue the "LEED O+M: Schools" credit and a second time to achieve at least 50% reduction on the site runoff, through the implementation of LID-BMP infrastructures;
c) Acquire the area and costs associated with the desired LID-BMP infrastructures implemented for both runs.

As such, the first step is to correctly identify each necessary Category land use or their respective Runoff Coefficient override value. Afterwards, the building pluviometric zone has to be identified along with the storm return period and duration. Finally, the correct number of divisions must be obtained in order for the software to work properly. These first steps will be studied in section 5.3.2.1 and will dictate the first half of the program results.

After running the first half of the software the obtained results are introduced in the second half as inputs. These include the Category areas and runoff coefficients, the storm's intensity and duration, and the initial runoff. Subsequently, in the first run the pursued LEED credit is selected while in the second the desired final runoff is indicated. In both runs the preferred LID-BMP and the software priorities must be specified. These steps will be studied in section 5.3.2.2.

After correctly running the software and acquiring the necessary results, the obtained values will be discussed in section 5.4.

5.3.2. Initial Conditions

As seen in the last section, the introduced inputs will determine the final software results. As such, much attention as to be given to these values, correctly determining which should be introduced. To better understand this process, this section was divided in both halves of the software.

5.3.2.1. First half of the software: Initial Runoff

The first inputs to be selected are the Categories land use or their respective override value. As seen throughout chapter 4 and 5, as well as Attachment A, there are three Categories which land use have to be determine: Roofs, Floors and Topography. For Roofs, the indicated value in the database (Table A.1 or section B.1) is 0.85 from a 0.75-0.95 interval. However, to compensate for the fact that the building has a completely flat roof, which slightly decreases the runoff coefficient, the value of 0.80 was utilized as an override. Next, the Floors adopted the "Business" land use which is 0.75. This land use was selected since the building is mainly comprised of offices and secretariats, which are typically related to this land use. Finally, the Topography adopted the "Lawn" land use with a runoff coefficient of 0.20.

Next, the storm related inputs (rainfall duration, return period and pluviometric zone) have to be determined. Starting with the return period, by following LEED's bibliography, and as seen in Attachment A, the chosen value was 10 years. This value is also in agreement with *Regulamento Geral dos Sistemas Públicos e Prediais de Distribuição de Água e de Drenagem de Águas Residuais* (Portugal. Laws 1995) which, in Article 210.º, indicates a minimum return period of 5 years. Afterwards, the selected duration was 10 minutes. This value is once again in agreement with the previous Portuguese regulation, Article 128.º, in which is stated that this value should range between 5 and 15 minutes depending on the zone inclination. Since the building site in fairly leveled, the mean range was selected. Lastly, by consulting the pluviometric zones in section 2.7, zone A was selected.

Regarding the last input for the first half of the software, the selected number of divisions was 20. This was the value chosen since it originated a spacing of around one meter, as suggested in Attachment A. All inputs for the first half of the software can be seen in Figure 5.6.

5.3.2.2. Second half of the software: LIDBMP

In the second half of the software most of the necessary inputs are values acquired from running the first half. As such, those values cannot be determine as of yet. Nevertheless, the remaining inputs regarding the LID-BMP and the chosen priorities can be defined. This way, as stated in the problem formulation, two runs were created. The first strives to achieve the "LEED O+M" credit by using the cheapest combination of Rain Barrels, Permeable Pavement and Green Roofs. The second tries to mitigate the initial runoff in 50% by using the same three LID-BMP but with a pre-determined priority order: Rain Barrels > Green Roof > Permeable Pavement. The maximum number of barrels, in both cases, is 10.

The inputs for the first run can be seen in Figure 5.7, while the inputs for the second run are presented in Figure 5.8.

5.4. Findings and Discussion

5.4.1. Initial runoff results

In this section the results obtained from the software runs will be briefly presented and thoroughly discussed, in order to prove the software accuracy and usability. As such, in Figure 5.6, it is possible to observe an initial runoff of approximately 50405 liters obtained from the first half of the software and other important values required for the second half of the program.

Fig. 5.6 – Results (in pink) obtained from the first half of the software

From these values, a few can be easily determined as correct simply by comparing the results with the information inside the Revit model and the database. For instance, when analyzing the Revit model Categories, it is possible to understand that at least the Roof and Topography Categories fully contribute to the runoff volume. As such, by comparing the Revit areas shown in Figure 5.5 with the ones from Figure 5.6, it is possible to understand that at least the areas concerning these two Categories are correctly determined. Furthermore, it is also understandable that the area displayed by the software for Floors has to be inferior to the one displayed in Figure 5.5, since the majority of this Category is not hit by the rain (mostly covered by Roofs). As such, this comparison between Figures 5.5 and 5.6 also gives a small verification for the Floor Area displayed by the software. However, by going a step further and analyzing Figures A.15 and A.21, it is possible to determine that the actual Floor elements are correctly selected (evidenced by the two rectangular grey shapes, projected from the above roofs, inside the blue Floor – Figure A.21) and that it is roughly superior to the Topography area. As such, these conclusions strongly corroborate the software results. Finally, when comparing the runoff coefficients inside the database, and also the ones overridden in the first half of the software, with the values displayed in Figure 5.6 (displayed as "RC"), it is clear that the used runoff coefficients were correctly obtained.

Despite all this, the above conclusions do not solely validate the initial runoff volume. To do so, the actual value has to be determined manually. As such, the following calculations serve as evidence to validate both the rainfall intensity and the rainfall runoff, by using equation 2.1 and 2.2:

$$I = a \times t^{b} = 290.68 \times 10^{-0.549} = 82.116\, mm/h = 0.0821\, m/h$$

$$\begin{aligned} Q = A \times C \times I &= (1882.625 \times 0.80 + 2338.719 \times 0.75 + 2115.008 \times 0.2) \times 0.082 \\ &= 3683.141 \times 0.082 = 302.018\, m^3/h = 302017 L/h \rightarrow 50336\, L \approx 50406\, L \end{aligned}$$

It should be stressed that the difference between the manually obtained runoff and the value displayed by the software is due to the software working with fifteen digits while the author only uses three decimal places in the manual calculations.

It should also be noted that despite the above runoff volume not representing the real runoff (since the model does not contain the laboratory), it still has a respectable accuracy for the real building since the workshop's roof absence is partially corrected by the use of 0.80 as the Roof's runoff coefficient, which is similar to the 0.75 Floor's runoff coefficient used in the area where the workshop should be.

5.4.2. LID-BMP RESULTS

As previously stated, for the second half of the software two different runs were implemented. In Figures 5.7 and 5.8 these run's inputs and results can be seen, respectively for the first and second runs.

Regarding the first run, and as mentioned in 5.3.2.2, the software tries to achieve the "LEED O+M" credit using the cheapest combination of these LID-BMP: Rain Barres/Cisterns, Green Roofs, and Permeable Paving. As such, the software indicates the use of 1844 square meters of Permeable Pavement as the sole necessary infrastructure. To validate this result three aspects must be covered:

The first is the verification that Permeable Pavement is in fact the cheapest LID-BMP. By analyzing the costs associated with the different LID-BMP in the LIDBMP.xml file in Attachment B, it is clear that Permeable Pavement is, by far, the measure that further minimizes the cost to achieve this LEED credit, resulting in a total of 119867.93€ (value confirmed in the calculations below).

$$Permeable\ Pavement\ Cost = Cost \times Area = 65 \times 1844.122 = 119867.93\ €$$

The second aspect is the area occupied. By analyzing this run's inputs, it is possible to verify that a total Floor area of 2338 square meters is introduced. As such, since the 1844 square meters associated with the Permeable Pavement are still smaller than the actual available area, this aspect is also validated.

Finally, the third aspect is the actual runoff volume mitigation. The “LEED O+M” credit demands the elimination of at least 25% from the initial runoff volume. This means that the Permeable Pavement needs to mitigate at least 12601.50 liters. By manually calculating the mitigated runoff the following is obtained:

$$Q(Permeable\ Pavement) = A \times C \times I = 1844.122 \times (0.75 - 0.25) \times 0.082$$
$$= 75.609\ m^3/h = 75609\ L/h$$

$$V(Permeable\ Pavement) = 75609 \times 10\ minutes \times {}^{1}/_{60} = 12601.500\ L \geq 12601.50\ L$$

To clarify, the subtraction in the above calculation translates the Floor’s runoff coefficient minus the Permeable Pavement’s runoff coefficient or, in other words, the coefficient associated with the runoff mitigation by Permeable Pavement.

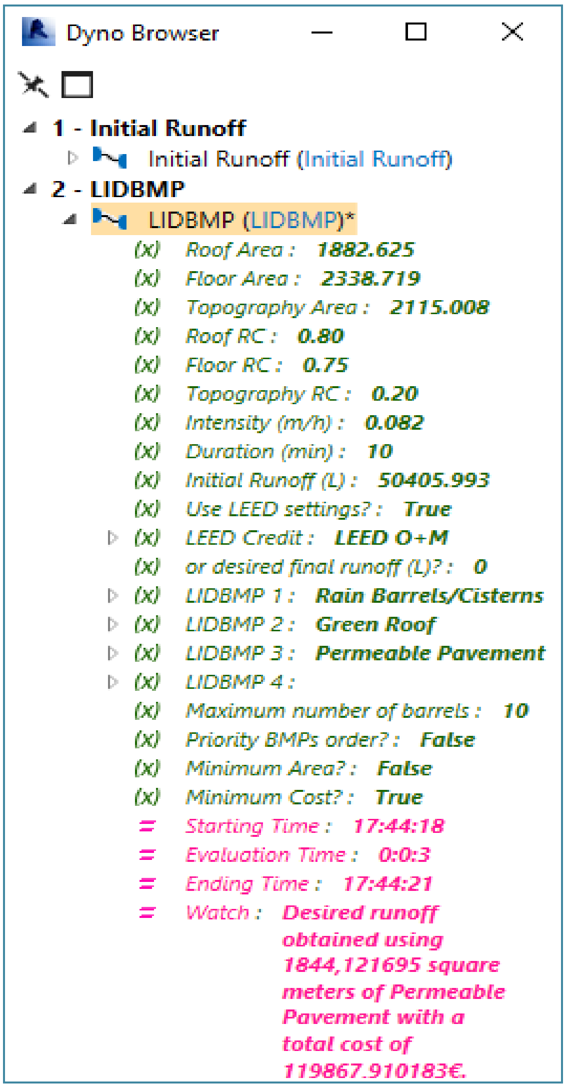

Fig. 5.7 – Results (in pink) obtained from the first run of the second half of the software

In the second run the necessary mitigated runoff is doubled from 25% to roughly 50% by manually introducing a desired final runoff of 25000 liters. Consequently, the Permeable Pavement is no longer able to solely mitigate the necessary runoff.

Since in this run the order in which the LID-BMP are introduced matters (Priority BMPs order? = True), the first LID-BMP used has to be the Rain Barrels/Cisterns, followed by the Green Roof and, finally, the Permeable Pavement. This is done in order to actually create a strategy behind the measures applied: the rainwater hitting the Roof is initially retained and mitigated by the Green Roofs, with the exceeding runoff being directed to the Rain Barrels for later reuse; meanwhile the rainwater hitting the Floors is almost fully stored and mitigated in the Permeable Pavement; lastly, the rainwater arriving at the Topography is naturally mitigated with the vegetation from the lawn. Any remnants of the runoff are directed to the already established stormwater infrastructure.

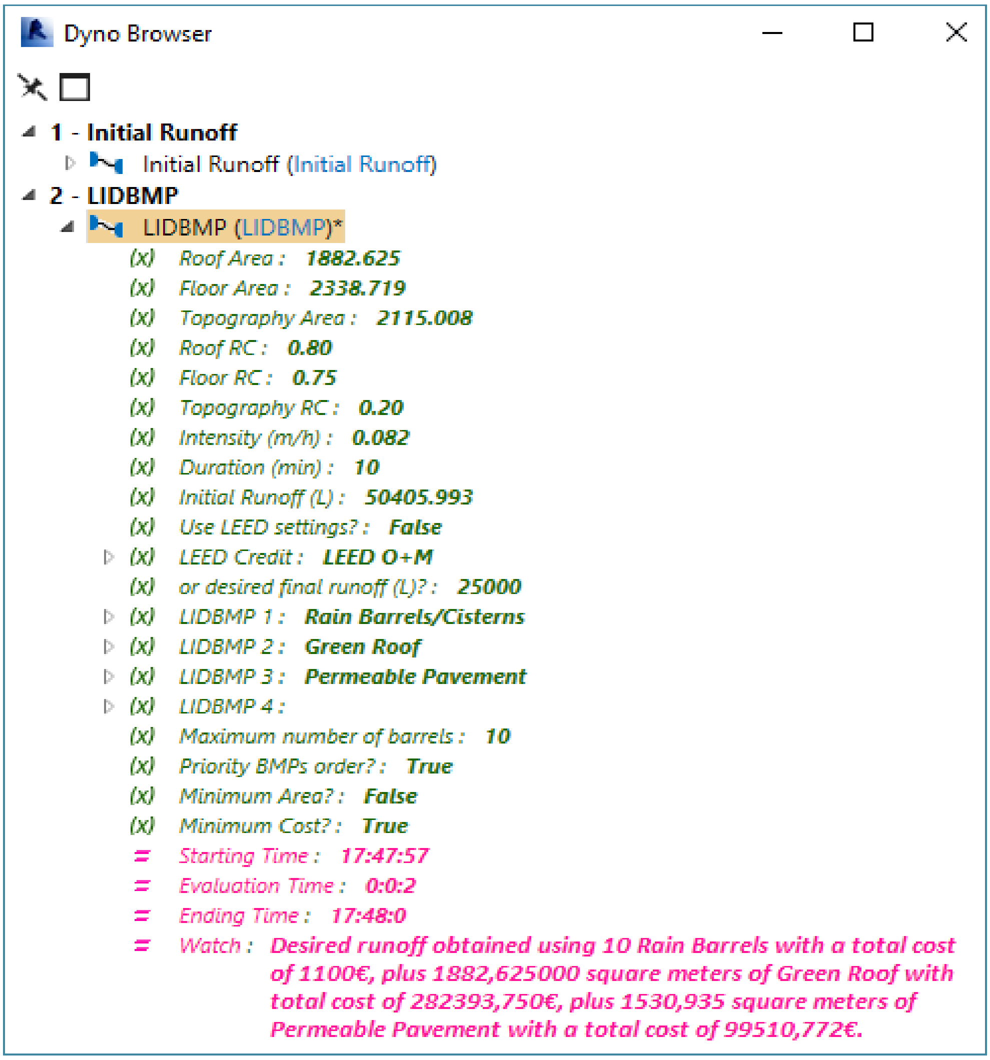

Fig. 5.8 – Results (in pink) obtained from the second run of the second half of the software

By solely reading the result description, it is possible to perceive this same order since both the Rain Barrels and the Green Roof use, respectively, the maximum number of barrels (10 barrels) and area (1882 sqaure meters) attributed to them.

Regarding the resulting cost, as expected, the final cost surpasses the total cost for the first run and is validated by the following calculation:

$$\begin{aligned} Total\ Cost &= 10 \times 110 + 1882.625 \times 150 + 1530.935 \times 65 \\ &= 1100 + 282393.750 + 99510.775 = 383004.53\ € \end{aligned}$$

Finally, the last verification for this second run is the actual volume mitigation which as to surpass 25406 liters to achieve the desired 25000 liters:

$$\begin{aligned} &Q(Green\ Roof + Permeable\ Pavement) \\ &\quad = [1882.625 \times (0.8 - 0.3) + 1530.935 \times (0.75 - 0.25)] \times 0.082 \\ &\quad = (941.313 + 765.468) \times 0.082 = 139.956\ m^3/h = 139956\ L/h \end{aligned}$$

$$\begin{aligned} &V(Rain\ Barrels + Green\ Roof + Permeable\ Pavement) \\ &\quad = 10 * 208 + 139956 \times 10\ minutes\ \times {}^{1}/_{60} = 2080 + 23326 = 25406\ L \end{aligned}$$

Following all the above conclusions regarding the software results, it is possible to infer that the software is working correctly, and that the initial objectives for this case study were achieved.

6
CONCLUSION

6.1. FINAL CONSIDERATIONS

At the end of this thesis it is possible to conclude that the initial proposed objectives were achieved. The two main topics of this thesis, Sustainability and BIM, were combined to automate LEED credits, contributing to the innovation of the LEED assessment system. Although this thesis focusses solely on the stormwater runoff related credits, it sought to generalize the idea that other credits can easily be automated. As stated in section 2.6, in the author's opinion, these LEED credits are amongst the hardest to automate given the wide range of inputs needed. In fact, other credits related to daylight, building orientation, carbon pollution, or even proximity to public services, can be easily determined by solely using the information stored inside the Revit model. However, it should be stressed that although most of these credits can be automated, some cannot. For these particular credits, which typically surround themselves with qualitative parameters instead of quantitative ones, intermediary software could be created to guide the user in their acquisition, alongside an expert practitioner.

Furthermore, it should also be noted that the relevance of the designed software was demonstrated not only by the StormWater Runoff features shown in the case study, but also from the assessment of the importance of sustainability certifications and their complexity and costs. This software also addresses the lack of technical programs aimed at the general user, carefully selecting the applied language and required inputs, giving special attention to the inputs attainability by the general public. However, thanks to the overriding system and the easily accessed and modified database, the software is also able to cater to the AEC Industry technical considerations, and can be used as an accurate design tool.

The case study focusing on the Civil Engineering Department of FEUP helped conclude that the software can be easily applied to any building with little effort, providing an accurate existent rainfall runoff and easily customable combinations of LID-BMP to diminish it. The task that could require more effort to successfully run the software would be the actual modeling of the building, however, by attaining a low LOD requirement, the model can be easily created.

During this thesis, it was also possible to determine the major efforts towards achieving a sustainable society. The conducted conferences, the existing frameworks and the LID-BMP are proof that these efforts have been correctly channeled towards sustainability, properly diminishing the negative impact society displayed at the economic, social and environmental levels. However, is was also perceived that these efforts are mainly attributed to developed countries, with developing countries paying close to no attention to the sustainability problem.

Regarding VPL, it is clear along this thesis that its simplicity and value has been unmistakably identified. However, it is the author's opinion that in the future these tools will not be used as a programming language to create complex software but mostly as an educational tool, or as a method to deepen the customization in technical programs (i.e. Revit and Grasshopper) and multimedia programs (i.e.

Blender). This is greatly attributed to the strong impediments these languages have, making it difficult or even impossible to properly optimize software.

In terms of difficulties found along the creation of this thesis, the most impacting ones are highlighted in the following list:

- Correctly modeling the Civil Engineering Department in Revit, by correcting a few wrong measures and properly linking the correct Categories and materials to the floors, roofs, walls and topography;
- Understanding the technical requirements behind LEED credits, mostly because this technical information is not publicly available as it is typically sold alongside LEED manuals;
- Achieving a consensus regarding the information and the values related to the LID-BMP, since most of these practices are still fairly new, with little empirical research available, with results that vary widely between them. The lack of studies analyzing these practices' performance for long periods of time greatly hindered the acquisition of operation, maintenance and repair costs along with long term efficiencies for LID-BMP;
- Obtaining a viable solution for the software interface and, after settling with Dyno, overcoming the many restrictions and bugs that this software still has;
- Overcoming many of Dynamo's node related bugs, which were expected since it is a fairly new programming language;
- Achieving a proper running time for the designed software, since Dynamo is quite poor in terms of optimization.

Nevertheless, it is the author's opinion that all the above mentioned difficulties were properly overcome.

Lastly, as of May 2016 part of the software's code was in 146.º place of the packages list in Dynamo's official website. The uploaded package contained approximately a quarter of the software's code, enabling the user who downloaded it to automatically obtain the areas for Floors, Roofs and Topography of any Revit model. The total number of packages present at the website is 796, which makes the uploaded code among the 20% most downloaded packages for Dynamo, with a total of 153 downloads and encouraging reviews. In the author's view, this strongly underlines the software relevance, which is even more emphasized by the fact that most of the uploaded packages are made from actual software companies charged with creating extra content for Dynamo.

6.2. FUTURE WORK

Following this thesis work, the natural future research could be divided in two major groups: the creation of other programs to automate the remaining LEED credits; and/or refine the already designed software. As such, the following points represent proposals that could be developed in future studies:

- Explore the remaining LEED credits and create software architectures that could handle their automatization – Credits such as "daylight management", "interior lighting", "acoustic performance", "thermal comfort", "water efficiency", among many others, are quite easily automated. In fact, software such as Tally^{R}, Solar Analysis and Green Building Studio, already determine the necessary information to obtain most of these credits despite not automating LEED certifications. Consequently, by analyzing these software and creating a proper program architecture, a new software connecting all these applications (possibly by means of the *cloud*) could be created to almost completely automate LEED;
- Further expand the database by including other countries IDF curves information – In order to decrease the user burden in using the designed software, the created database could be gradually

expanded along the next few years, by first integrating countries with easily defined pluviometric zones (i.e. United States of America, Australia, New Zealand, India, Argentina) and then opting to use the actual IDF curves, from countries with no clear defined pluviometric zones;

- Introduce other LID-BMP solutions in the software – Despite the software already containing most solutions regarding runoff quantity, other practices, primarily focused on runoff quality, can also be implemented. This could not only increase the software diversity and customization in terms of solutions, but also be the first step towards automating other LEED credits, in this case, the ones related with runoff quality;
- Upgrade the software to also indicate most LID-BMP characteristics such as soil width, plant species, extensive/intensive green roof, slope inclination, among other – This would contribute not only to the result enrichment but also to its accuracy, since a more precise range for runoff mitigation and cost, could be determined by considering these LID-BMP characteristics;
- Renew the created interface in Dyno – Update or possibly redo the entire software interface, designing a new one in C# or Visual Basic, in order to eliminate the current dependence of the StormWater Runoff program on a software that still remains in beta phase;
- Develop more effective methods towards a greater software optimization – Since the “node” systems implies a few restrictions towards the projected software capabilities, “code blocks” and Python could be used to achieve a greater software speed and customization.

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ATTACHMENT A

SOFTWARE CODE AND DYNAMO CONCEPTS

In this attachments the actual Dynamo code behind the StormWater Runoff software is explained. To do so, the attachments were divided into three main parts. The first two clearly explain the designed software architecture: the first covers the acquisition of the initial runoff, and the second focus on correcting that runoff. The third and last section explains “lacing”, an important concept behind most of the Dynamo nodes. Also, throughout the code explanation the Revit model used in the case study will be shown alongside the placed nodes for a better understanding of what the software is actually computing. However, some results are not the same as the ones displayed in the case study since in this explanation the overriding value used for the Roof was 0.75 and not 0.80.

A.1. OBTAINING THE INITIAL RUNOFF THROUGH DYNAMO

A.1.1. COLLECTING ROOFS, FLOORS AND TOPOGRAPHY

The first step on obtaining the initial rainfall runoff is to actually import the necessary Categories from Revit to Dynamo, in order to retrieve their information. As such, a connection between the two software has to be made. As stated previously, this connection is offered by Dyno and was thoroughly discussed in chapter 4.5.

After establishing this connection, it is necessary to choose which categories and respective elements are going to be addressed. In this case, since the objective is to determine the area that actually contributes to the rainfall runoff, it is required that not only all the Roofs, but also all the Floors and Topographies are retrieved from the Revit model. In Figure A.1 it is possible to understand how this procedure is completed for the Roofs and Floors, using the “Categories” and “All Elements of Category” nodes.

Once this first step is completed, each element altitude (from Roofs and Floors) is retrieved using the “Element.GetParameterValueByName” node (also seen in Figure A.1). However, since each Category has different parameter names inside Revit, to obtain the same information, the parameters “Level” (for Floors) and “Base Level” (for Roofs) are required. As such, the floor number and its respective elevation are retrieved for each element. This information is then synthesized using the “Level.ProjectElevation” node that not only retrieves the elevation from the information previously acquired, but also turns it into a zero based list with a single column and “n” rows, where “n” is the number of elements.

With the previous steps the software creates two central lists to be used in the next sections: the first, retrieved from the “All Elements of Category” node, contains both Roofs and Floors ID’s and the second, retrieved from the “Level.ProjectElevation” node, contains both Roofs and Floors elevations.

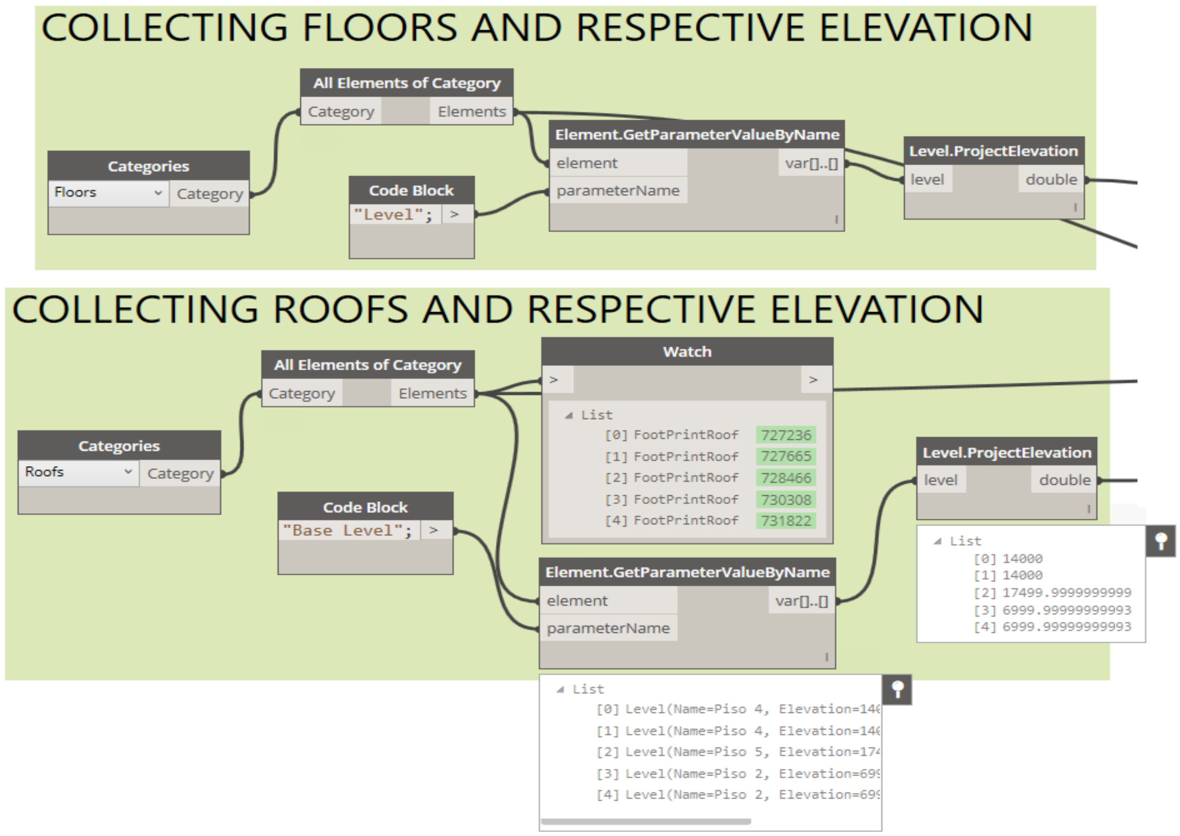

Fig. A.1 – Created Dynamo code for collecting Floors and Roofs

Finally, gathering the topographic information inside BIM is done in the same manner as the first step of this section. However, since the Topography Category does not contain altitude related information, it is necessary to retrieve the points forming this element through the "Topography.Points" node and form a polygon using the "Polygon.ByPoints" node. This polygon is then used to obtain its linked surface, using the "Surface.ByPatch" node, so that later, information such as the Topography area can be retrieved and the surface color can be override (see section A.1.9 and A.1.10 for better comprehension) to better perceive which elements are been used by the Stormwater Runoff software. This whole process can be seen in Figure A.2.

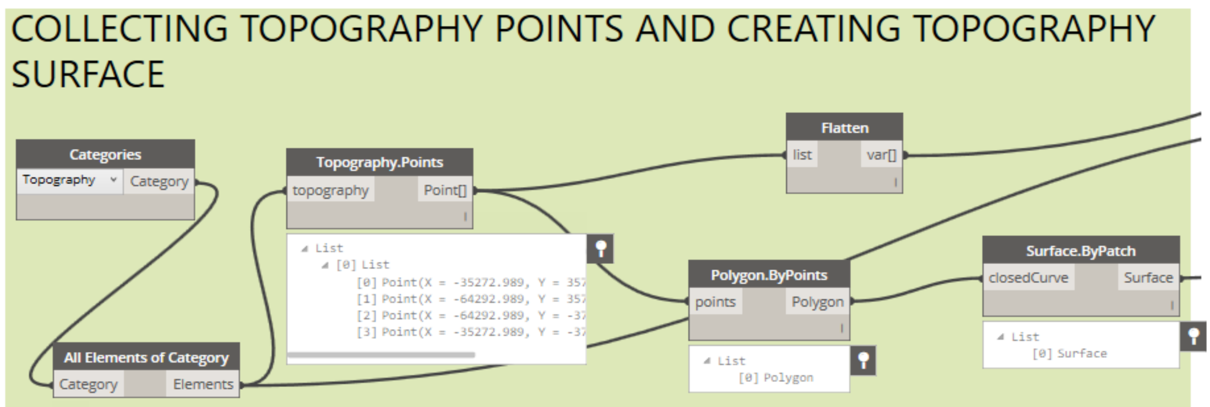

Fig. A.2 – Created Dynamo code for collecting Topography

A.1.2. LISTING THE INFORMATION

After gathering all the necessary information, it is essential to list it into a single node to facilitate its manipulation and increase the software processing speed. To better understand the reasons behind this listing check section A.1.6.

In this step the first elements to be treated are the Roofs and Floors. This way, the lists retrieved in the previous sections, through the "All Elements of Category" and "Level.ProjectElevation" nodes, need to be manipulated. However, closely analyzing these lists it is possible to understand that they are comprised of two columns (the first for Floors and the second for Roofs) and "n" rows ("n" being the greater number between the total count of Roofs and Floors). In order to proper manipulate these lists, both lists are "Flatten", obtaining two lists with only one column and "m" rows ("m" being the sum of Roofs and Floors).

Using the list containing the elevations as a "key", the first list is sorted using the "List.SortByKey" node. As such, a list containing the Roofs and Floors ID's sequenced from the lowest to higher elevation is created. This list is then reversed using the "List.Reverse" node with the sole purpose of shifting the order of the list to speed the software and better understand which elements are at a superior elevation. This list is then joined with the Topography ID, obtained in A.1.1, using the "List.Join" to place it on the bottom of the list where it belongs, since Topography is typically the lowest Category in term of altitude.

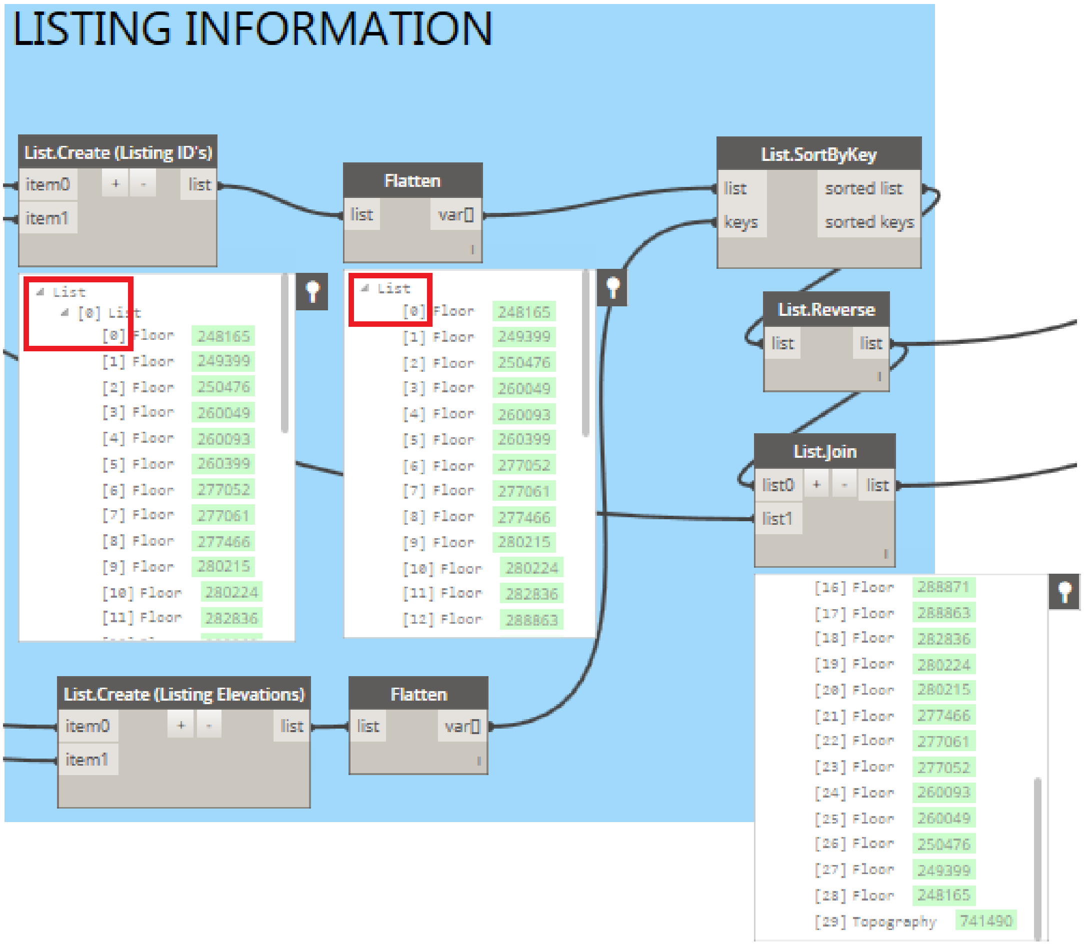

Fig. A.3 – Created Dynamo code for listing retrieved elements. Emphasis given to the flatten process (red boxes)

A.1.3. Obtaining maximum and minimum coordinates

In this next section, the minimum and maximum coordinates for all the elements obtained must be retrieved in order to simulate a bounding box for the Revit model. This bounding box will then be used in the in section A.1.4. To do so, two steps must be taken. The first gathers all the vertices from the retrieved Floors and Roofs into a single list (Figure A.4). The second joins this list with the Topography points retrieved in section A.1.1, and also the maximum and minimum coordinates for all the obtained vertices are acquired (Figure A.5).

In order to complete the first step the “Element.Faces” node is applied. This node requires the input of an element in order to subdivide it into surfaces. As an example, introducing an element chapped as a cube would create 6 surfaces. However, a pivotal aspect of this node is the order in which this surfaces are created. In fact, the order is not random, the surfaces are always created and listed from top to bottom of an element. This means that the first surface, contained in the [0] index, is always the topmost surface of the element or, in other words, the surface facing upwards. As such, this is the surface required for the calculation of the rainfall runoff, since it is the one influencing the area exposed to the rain.

Using this vital information, after creating the list containing all the surfaces with the “Element.Faces” node, the “List.GetItemAtIndex” node is used as a function to retrieve the [0] index from the surfaces list. Functions in Dynamo can be created by not connecting information to some or all (depending on the node) of the input ports of a determined node. This node can then be connected to an input port requiring a function [f(x)], such as “List.Map”. However, it should be noted that the majority of nodes cannot be used as functions. Functions, like in traditional programming, create cycles. In this case, the “List.GetItemAtIndex” node, used alongside the “List.Map” node, cycles the entire surfaces list in order to retrieve all the surfaces contained inside the [0] sub-indexes.

These retrieved surfaces are then introduced into the “Topology.Vertices” node that simply retrieves all the vertices from a topology, in this case, the various surfaces. These vertices are then connected to the “Vertex.PointGeometry” node, which translates the vertices into geometry points. To end this first step, the list containing these points is “Flatten”. The created Dynamo code for this first step can be seen in Figure A.4.

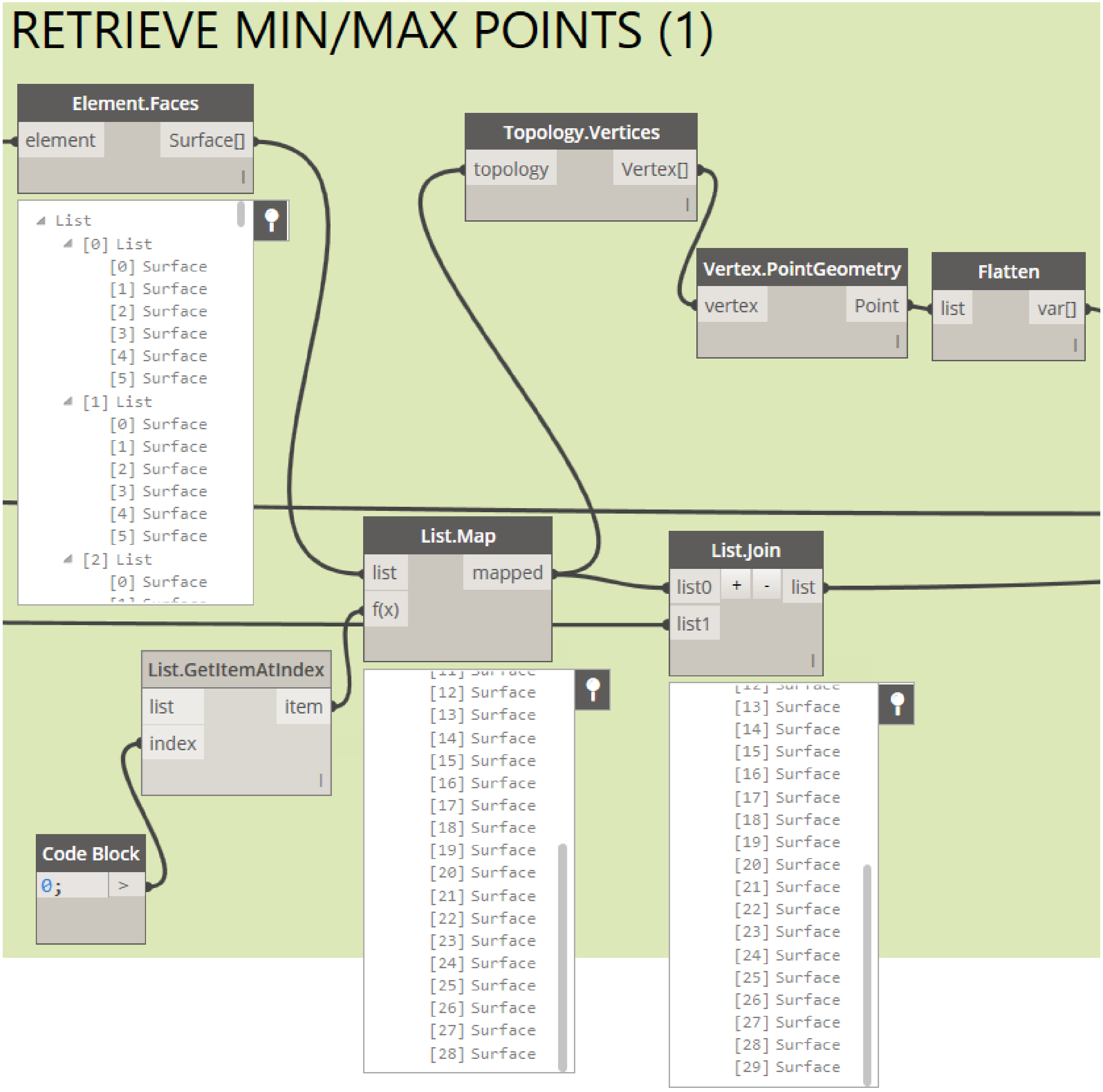

Fig. A.4 – Created Dynamo code for retrieving the Roofs and Floors vertices

In the second step the retrieved vertices points are joined with the Topography vertices acquired in section A.1.1. This is done using a simple “List.Join” node. At these point, the software then uses the created list, holding all the element vertices coordinates, alongside the “Point.X”, “Point.Y” and “Point.Z” nodes, to isolated the coordinates into three lists: one containing all the X coordinates; another containing all the Y coordinates; and finally one containing all the Z coordinates. By applying the “List.MinimumItem” and “List.MaximumItem” nodes, the minimum and maximum values inside these three lists are retrieved, obtaining the 6 necessary points to simulate the bounding box used in the next section. Furthermore, the absolute value for the minimum Z coordinate is also obtained using the “Math.Abs” node, in order to sum it with the maximum Z coordinate, through the use of a “Code Block”, resulting on the acquisition of the model height. The created Dynamo code for this second step can be seen in Figure A.5.

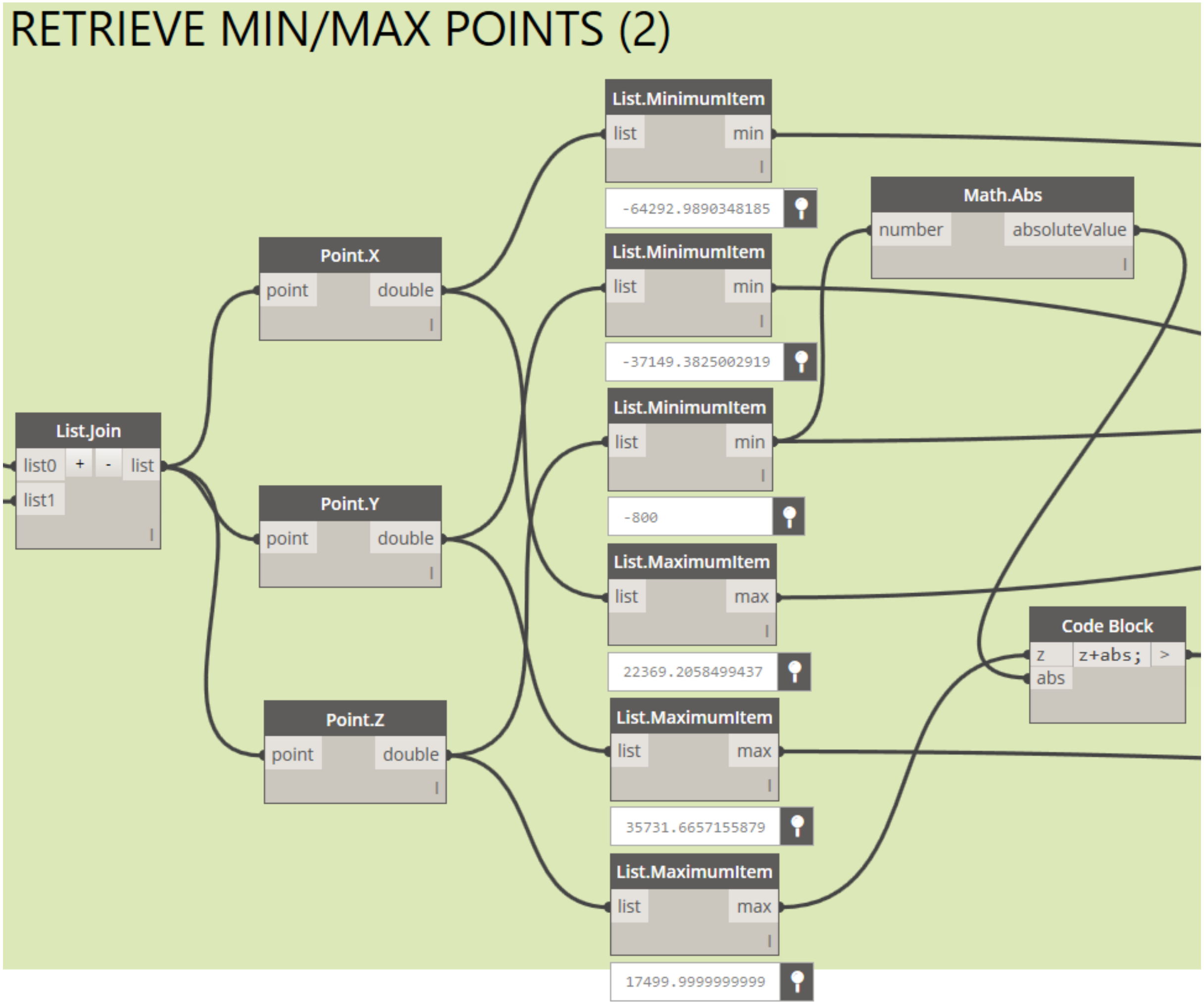

Fig. A.5 – Created Dynamo code for retrieving the minimum and maximum coordinates for the Revit model

Finally, before continuing to the next step, the retrieved Roofs and Floors top surfaces are joined with the Topography surface created in A.1.1 in order to be introduced in the "Geometry.Intersect" node in section A.1.5.

A.1.4. Creating "Rain lines"

After successfully obtaining the maximum and minimum coordinates for the Revit model, it is time to simulate the rain in order to retrieve the elements that actually contribute to the rainfall runoff. As such, using the previously acquired coordinates a grid of vertical lines is created. This grid encompasses the entire volume inside the Revit model, since it is created over the "bounding box" created in the last section.

To create this grid, the first step is to acquire the base of the Revit model. To do so, two "Code Blocks" were used containing the following code: "Min..Max..#Lines". The purpose of these nodes is to create two different lists containing a set of numbers that go from the "Min" input to the "Max" input, a number of "Lines" times. The "Min" and "Max" values introduced in this node correspond to the minimum and maximum X and Y coordinates previously obtained. As seen in Figure A.6, the X coordinates are connected to the upper “Code Block” while the Y coordinates are connected to the lower one. The value “Lines” is introduced by the user through Dyno (seen in Dyno as “Number of Divisions”) and represents the actual number of lines created in a determined axis. It is recommended that the introduced value creates a spacing of around one meter between vertical lines, inside the Revit model.

After obtaining these two number sequences the base of the grid can be created using the “Point.ByCoordinates” node. By introducing the number lists in the X and Y inputs, two rows of points are created in the Dynamo canvas (one parallel to the X vector and another to the Y vector). Connecting the minimum Z coordinate previously acquired to this node moves the created rows to the correspondent Z plane. By switching the node to offer a “Cross Product” lacing the base of the grid is created (to better understand lacing see Attachment A). This grid base will serve as the starting points for the “rain lines”.

To acquire the endpoint for these lines, the same procedure could be used. However, creating points is a task that consumes a considerable amount of time for Dynamo. As such, to speed the software, instead of creating new points, the ones already created are copied and moved to the desired place. As such, the “Geometry.Translate” node is used alongside the “Vector.Scale” node. The first node carries a certain geometry (in these case the created points) while the second specifies the direction and distance to transport. To obtain this direction and distance two simple inputs have to be introduced: a vector and a scale factor. The first is obviously the Z axis since the lines need to be vertical; and the second corresponds to the maximum Z coordinate previously retrieved. This way, by connecting all these nodes, the endpoints are created and introduced in the “Line.ByStartPointEndPoint” node, resulting in a grid of vertical lines (Figure A.7). These lines will represent the pouring rain over the building site.

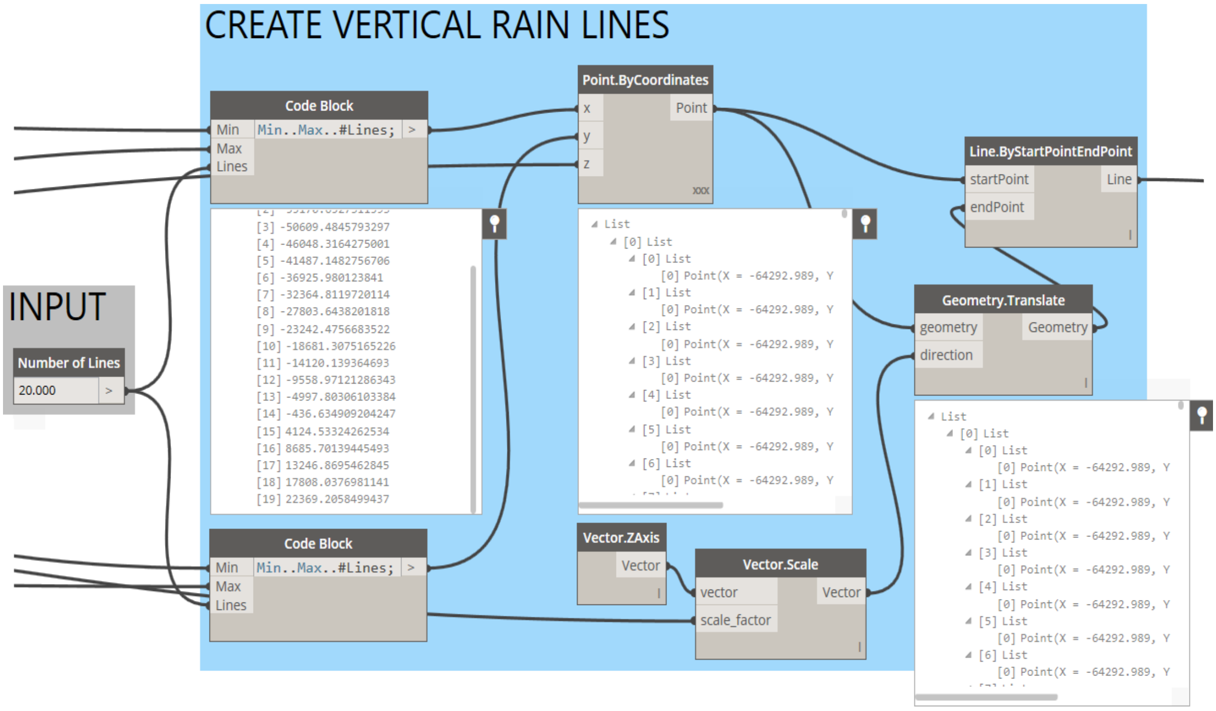

Fig. A.6 – Created Dynamo code for creating “rain lines”

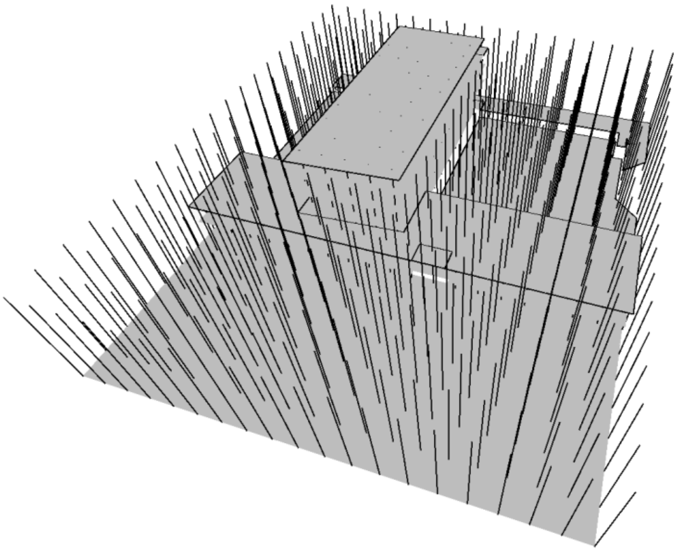

Fig. A.7 – Creating the “rain lines” inside Dynamo and Revit

A.1.5. INTERCEPTING “RAIN LINES” AND VISUALIZING THE INTERCEPTION

In this next section the “rain lines” created in the last step will be intercepted with the retrieved elements from Revit. To do so, both the node containing the surfaces from the elements (visible in Figure A.4) and the node containing the vertical lines (visible in Figure A.6) will be necessary.

The first step in this process is to connect the created lines to a “List.Map” node after flattening the list containing them. In order to obtain the surfaces intercepted by these “rain lines” the node “Geometry.Intersect”, which is linked to the surfaces list, is used as a function. This way, by connecting the “List.Map” node to the “rain lines” and the “function” “Geometry.Intersect” containing the element surfaces, a cycle is created in which the “rain lines” try to intercept the created surfaces one by one. However, this means that even if a “rain line” cannot geometrically intercept an element, the process of trying to intercept it will be processed. This way, if an interception is found, a point is created, if not, the list stays empty. This results in a great burden for the software and, thereby, methods to speed this process were experimented. The most promising was the elimination, from the geometry list, of all the elements that could not possibly be further intercepted by any “rain line”. This was done by analysis the next “rain line” coordinates in the series and comparing it to the elements coordinates. However, although successful, the process of doing verifications such as the one previously stated took an even greater toll on the computer, slowing the software performance. Yet, it should be stressed that this methods were tried on medium sized models as the one presented in the case study and could have positive outcomes when used in bigger Revit models where optimization process have a greater impact.

After acquiring the list of interceptions, in order to better perceive this procedure, small spheres are created in the topmost interceptions. To do so, two more functions are used: the first “Flattens” the list and the second retrieves the point with the highest Z coordinate in the same line or, in other words, the first interception with the topmost element. This is done by using the “Point.Z” and “MaximumItemByKey” nodes.

Finally, the data is cleaned from nulls and empty interceptions using the “List.Clean” node, and spheres with a thousand unit radius centered in the retrieved points are created using the “Sphere.ByCenterPointRaidus” node.

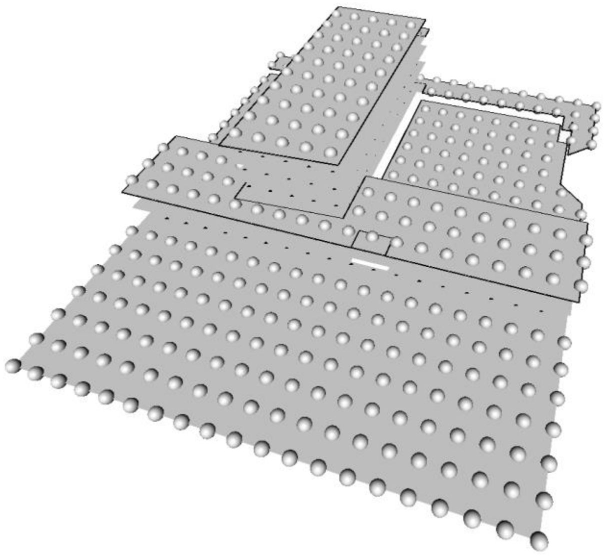

Fig. A.8 – Displaying the interceptions inside Dynamo

This full process can be seen in Figure A.9. Special attention should be given to the number of rows in the list offered by the "List.Map" node. In this example, there are 400 main indexes, each one having 30 sub-indexes inside. These represent the 20*20 "rain lines" created in A.1.4 (Figure A.6) and the 30 surfaces retrieved from the Revit model in A.1.1.

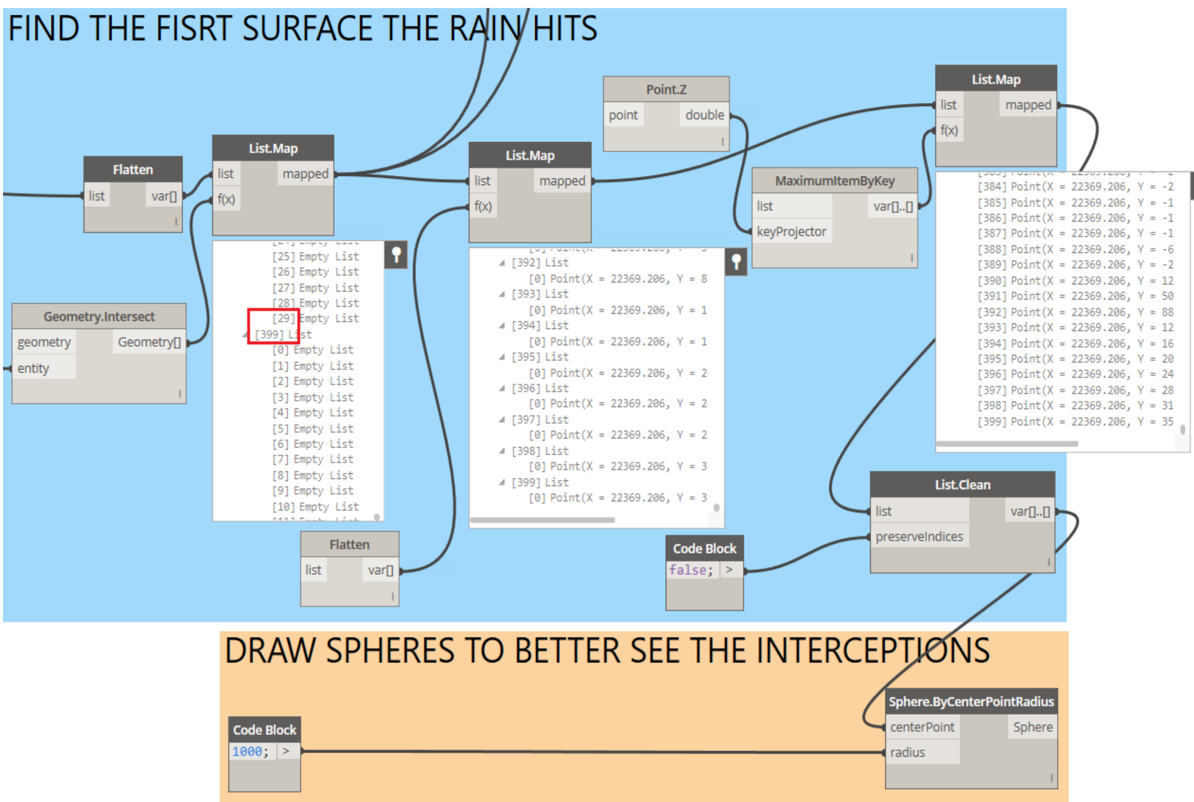

Fig. A.9 – Dynamo code for intercepting "rain lines" and surfaces while also improving the interception visualization

A.1.6. OBTAINING THE TOPMOST ELEMENTS HIT BY THE “RAIN LINES”

In the previous section it was possible to visually identify which elements where being hit by the rain through the creation of spheres. However, the actual elements were not retrieved and saved in a separate list inside Dynamo. In this section, this exact procedure will be conducted through the use of the “List.Combine” node. This node combines two or more list using an introduced parameter. In this case, that parameter is the “in” port of the “List.FilterByBoolMask” node or, in other words, the “true” values. As such, a Boolean list is needed to do the actual combination.

Since the objective is to retrieve the topmost intercepted elements, the list containing them will be utilized. This list is offered by the first “List.Map” node seen in the previous section. However, this list contains only empty values and interception points, which are not Boolean. In order to “translate” this list to Boolean values the “List Not Empty” node is used in conjugation with the “List.Map” node to create a function. This function is then linked to another “List.Map” node which in turn is connected to the list containing the interceptions. As such, the interceptions list is checked for empty values: assigning “false” for empty rows and “true” for the opposite. This way, all the interceptions acquire a “true” value in the newly created Boolean list.

The second list needed for the combination node is the actual elements list. However, both list need to have the same size in order to be combined using a Boolean function. As such, the 30 elements list is repeated 400 times using the “List.OfRepeatedItem” node. This node repeats a certain item, in this case the element list, a determined number of times, in this case 400. The actual number of repetitions is acquired using the “Count” node linked to the interception list. This node counts the number of main indexes inside a list, thus giving the necessary amount of repetitions. This way, a second list is obtained, containing 400*30 rows, just as the interception list.

Finally, since both the interceptions list and the repeated elements list were created with the same elements in the correct order, by using the “List.Combine” node the interception points will always correspond to the correct element in the elements repeated list. This results in the acquisition of all the elements that are intercepted.

However, as previously seen in A.1.5, the same “rain line” might intercept various elements. Yet, the wanted elements are the ones with the higher elevation. As such, since in section A.1.2 the elements list was organized from the highest element to the lowest, the first element (inside index [0]) will always be the highest. As such, the same procedure used in A.1.3 is applied to retrieve the elements contained in these indexes. The resulted list, only containing the highest intercepted elements, is then filtered using the “Manage.RemoveNull” node, to remove any null values originated from lines that might not intercept any element.

This full procedure can be better understood through the representative index [312] in Figure 4.12.

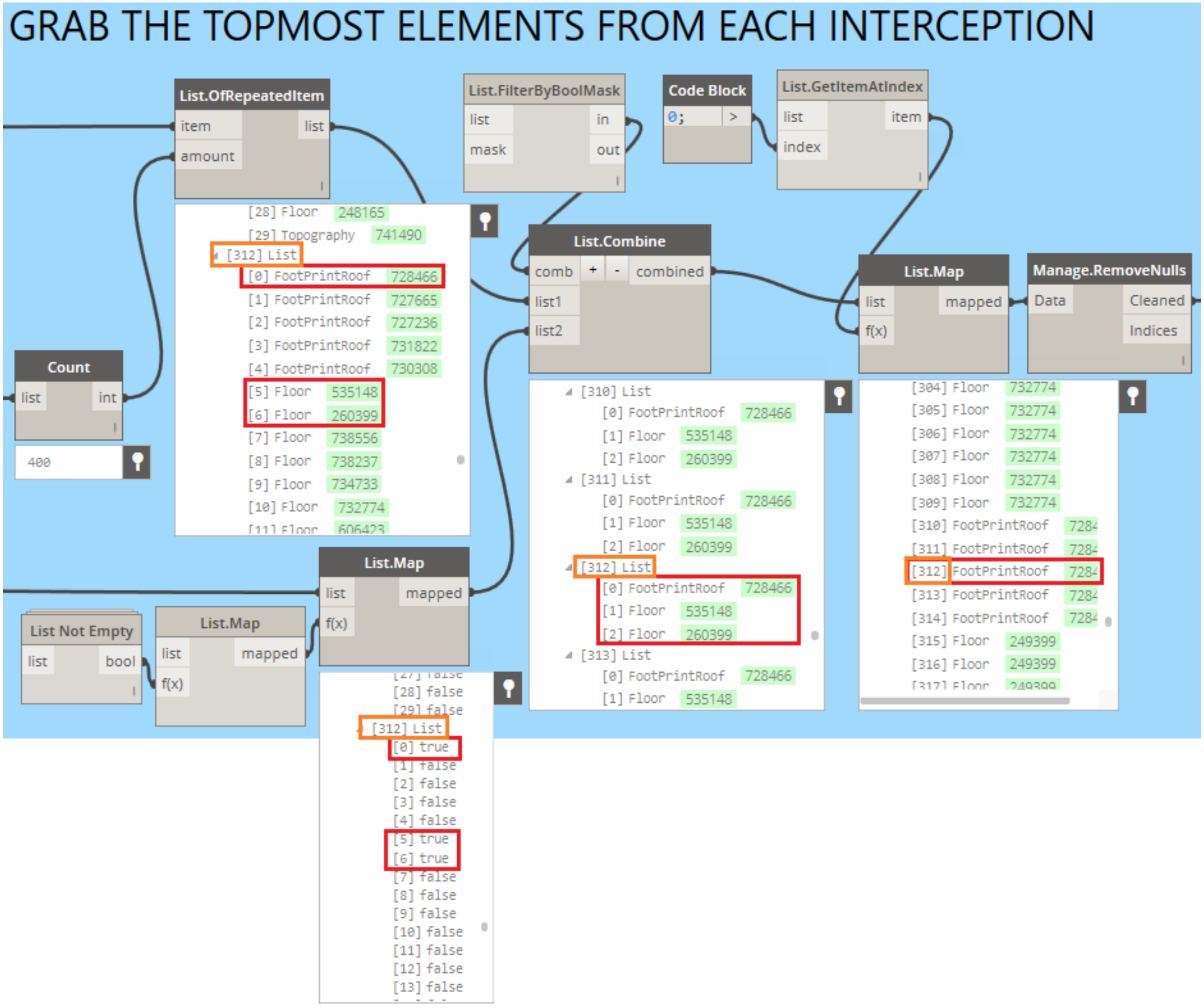

Fig. A.10 – Created Dynamo code for retrieving the topmost intercepted elements

A.1.7. Retrieving unique elements and separating them

As seen in the previous section, after obtaining the topmost elements hit by the "rain lines", a list containing these geometries is created. However, in order to efficiently use this list and manage its information, the repeated data, in this case, the repeated elements, must be eliminated. To do so, the "List.UniqueItems" node is used. This node simply cycles any given list, saving unique elements and comparing them to the rest (obviously, the first element in a list is always labeled as unique). If the comparison is false, the compared element is also saved as unique, if the comparison is true, the compared element is eliminated. The result of this process can be seen in Figure A.11, on the "Watch" node.

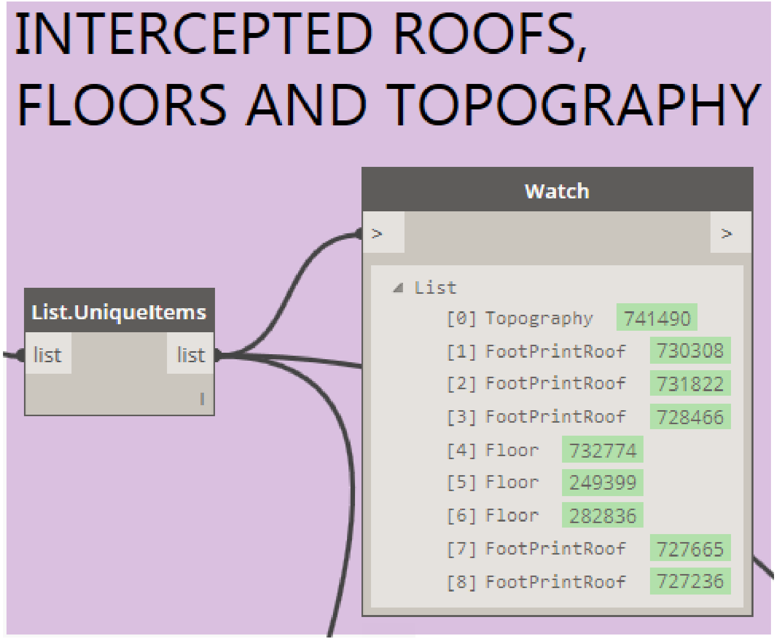

Fig. A.11 – Obtaining the unique topmost elements hit by “rain” in Dynamo

After the unique elements are retrieved they need to be separated in three lists, each containing a different Category: Topography, Floors or Roofs. However, Dynamo still does not possess a node for comparing this list content and separate the data into three lists. As such, to be able to manage this information the previous list needs to first be converted into a string. Using the “String from Array” node the list containing all the elements visible in the “Watch” node is converted into a single text line. Then, by having the list into a string, the “String.Split” node can be used to separate it into various elements (the separators being “}”, “{” and “,”). As seen in the preview box below the last node, the result is an exact replica of the list retrieved from the “List.UniqueItems” node with the exception of being in string format. This way, it is possible to use the “String.Contains” node to search for any word inside the created list. Using this node, it is possible to generate a bool mask containing the result (true or false) between the comparison of an introduced search word and a given string list. Using this mask alongside the elements retrieved from the previous “List.UniqueItems” node, by using the “List.FilterByBollMask” node it is possible to separate the searched element from the rest. This way, the elements are separated into three different lists.

As seen in Figure A.12, the elements are separated using the respective Category. The first separated elements are the Floors, retrieved through the “in” output port in the first filter node, leaving the two remaining Categories (Roofs and Topography) in the “out” output node. In order to separate them, these two Categories are once more submitted to the full procedure, this time searching for Roofs.

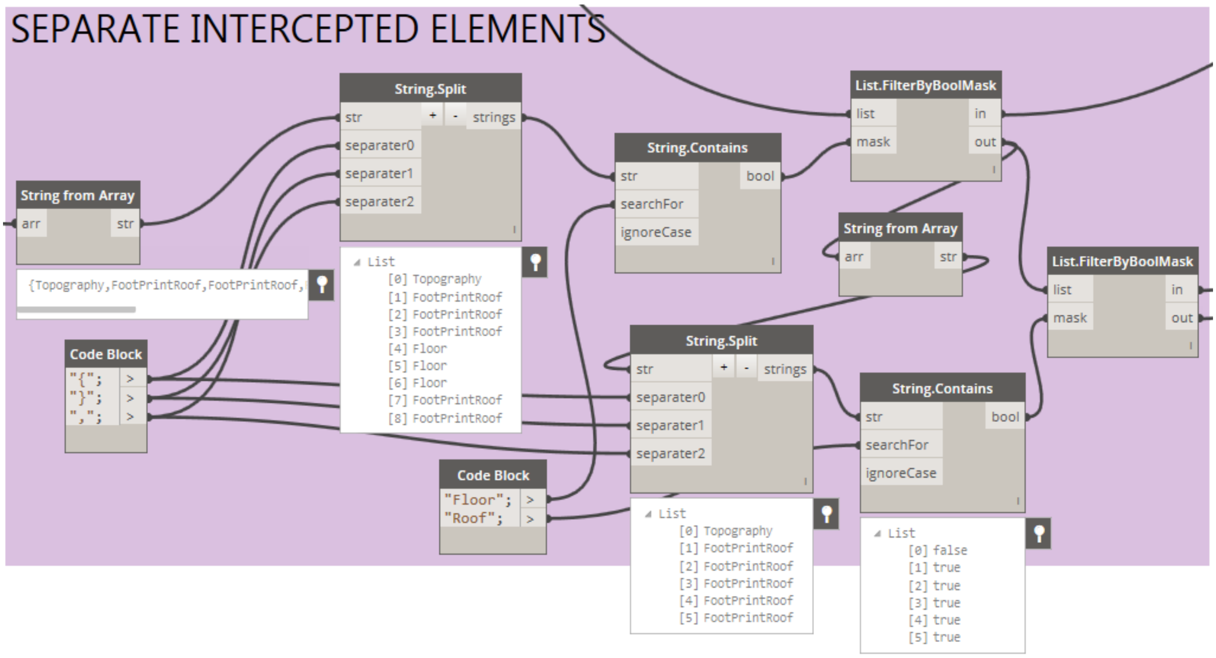

Fig. A.12 – Created Dynamo code for separating intercepted elements

A.1.8. Separate the portion of area hit by rain from the area that is covered by other surfaces

In the previous sections it was possible to obtain the elements exposed to the rain. To do so, the topmost elements being intercepted by the “rain lines” were retrieved. However, in this process, no attention was paid to which parts of these elements were actually being hit by the rain. In this next step, in order to retrieve this desired areas, these elements will be further analyzed. The software will basically create a vertical wall outlining the selected elements, splitting any element that is sliced by this wall and retrieving the areas that still get hit by the rain.

The first step in obtaining these areas is finding the elements perimeter curves. To do so, the “Surface.PerimeterCurves” node is used. As the name suggests, this node retrieves the circumventing lines for an introduced surface. As such, the elements surfaces have to be inputted in the node. However, these procedure only requires Floors and Roofs since most Revit models already have the Topography “involving” the actual model and not trespassing it. This way, by using the same method as in A.1.3, a list containing the previous stated elements is created and their top surface is retrieved. These surfaces are then introduced inside the “Surface.PerimeterCurves” node, resulting in the acquirement of their perimeter curves. In Figure A.13 it is possible to check the Dynamo code responsible for this procedure.

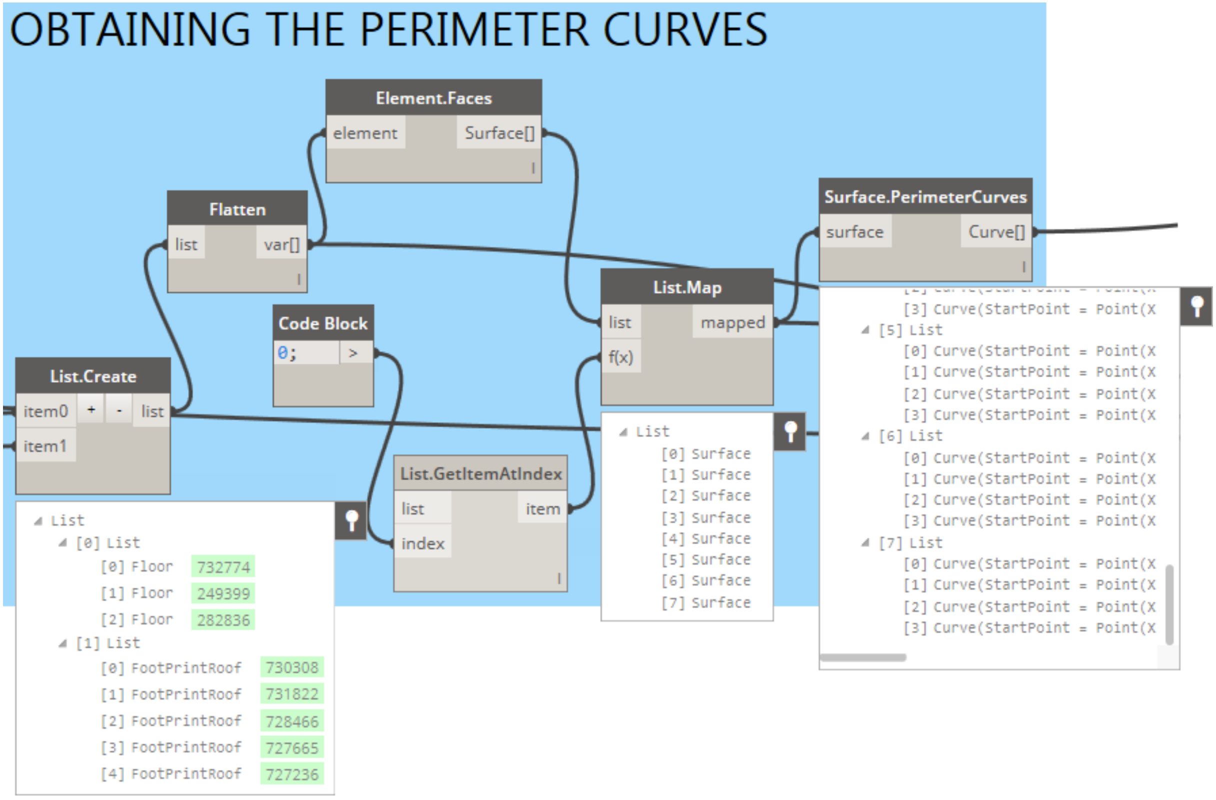

Fig. A.13 – Created Dynamo code for retrieving perimeter curves

After obtaining the perimeter curves, they need to be extruded in order to create the "vertical wall" that splits the elements. This is achieved by using the "Curve.Extrude" node. This node requires three inputs: a curve, a direction and an extrude distance. Using the curves already created and the Z axis as the pretended direction, the only input left is the distance. To allow the topmost elements to split the bottom elements the minimum distance required is the actual height of the Revit model obtained in A.1.3. However, the value must be negative in order to direct the wall towards the bottom of the model. This results in the creation of various vertical surfaces as seen in Figure A.14 and A.15.

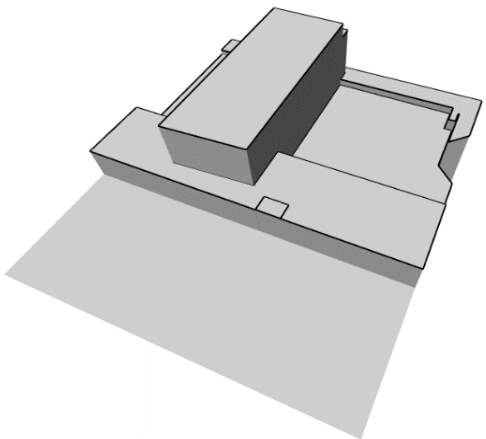

Fig. A.14 – Frontal model view inside Dynamo

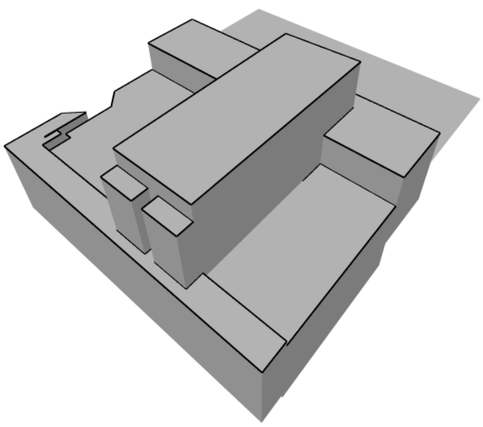

Fig. A.15 – Rear model view inside Dynamo

These surfaces are then used alongside the “Geometry.Split” node as the needed “tool” to split the “geometries” introduced. These geometries correspond to the Roofs and Floors surfaces previously listed and “Flatten” in Figure A.13. With this, the geometries are split and the ones which still get hit by the “rain lines” are retrieved.

Afterwards, a list containing the areas from these surfaces is obtained using the “Surface.Area” node. This list is “Flatten” and reordered alongside the elements previously listed, in order to not only greatly improve the software speed but also check if the areas retrieved from Revit have already been updated.

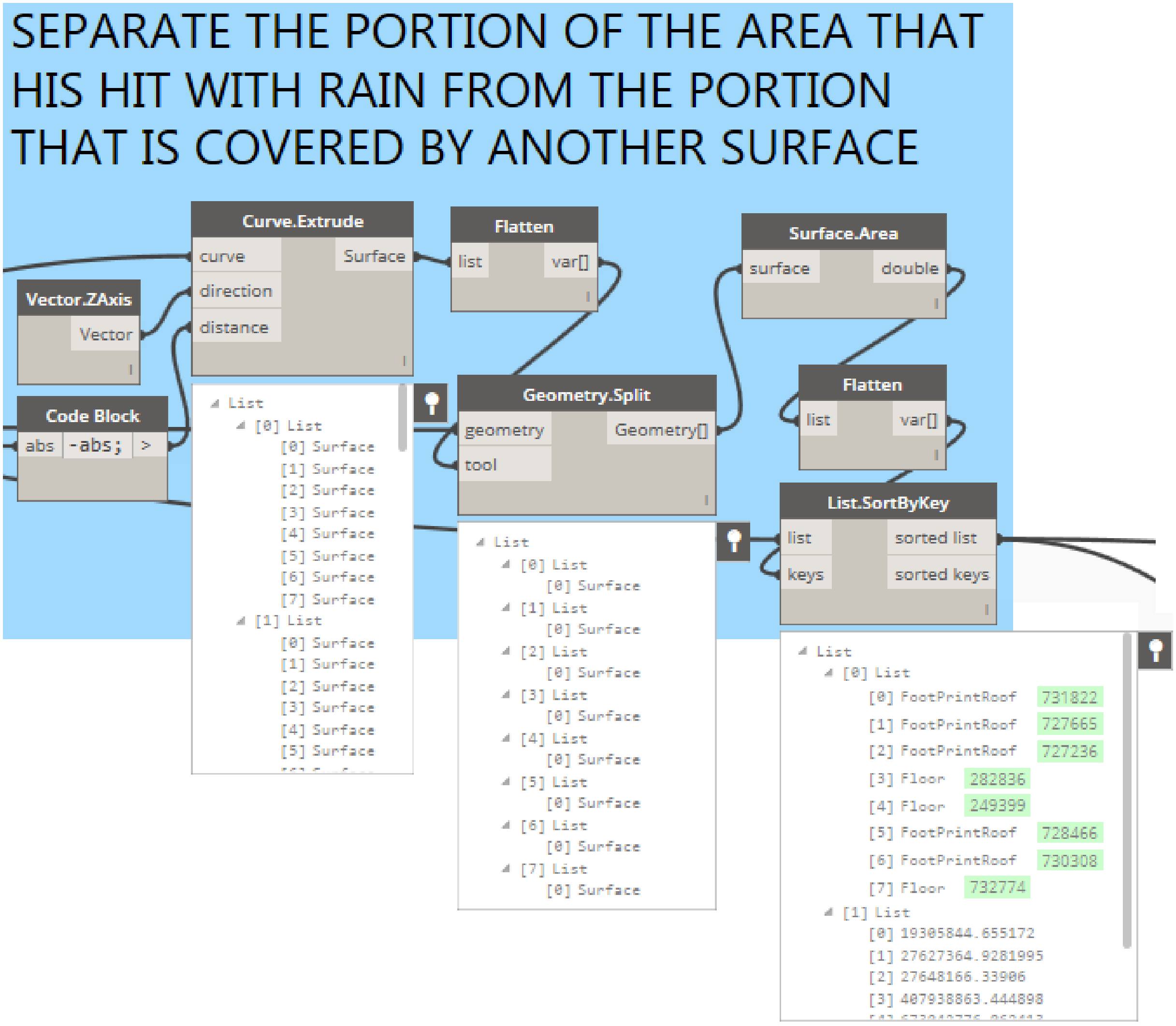

Fig. A.16 – Created Dynamo code for splitting the retrieved elements

After obtaining this list, the newly retrieved Roofs and Floors are separated using the same process as in A.1.7, creating two Category lists containing the corrected elements contributing to the rainwater runoff. The Topography Category had already been correctly separated in A.1.7 since it did not need any area adjustments. The resulting lists can be seen in Figure A.17.

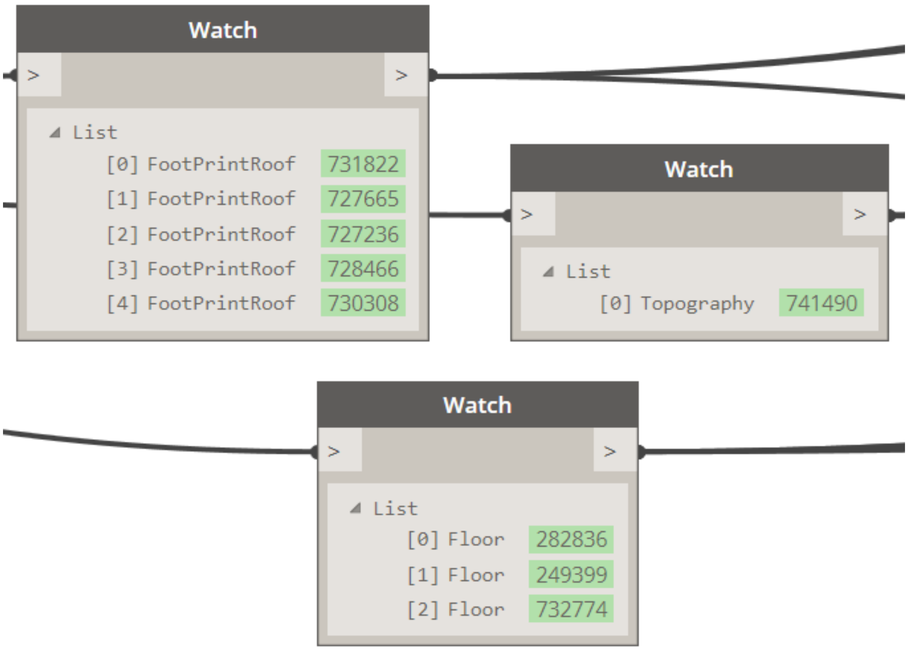

Fig. A.17 – Analyzed elements listed by Category

A.1.9. Retrieving the area from each element and displaying it on Dyno

In this next section, the area from the final acquired elements is retrieved and displayed in Dyno. To do so, the same node used in A.1.1, "Element.GetParameterValueByName", is used with different inputted parameter names. In order to retrieve this information the used parameters are "Area" for Floors and Roofs and "Surface Area" for Topography. However, as seen in Figure A.18, the obtained area corresponds to each individual element and not the global area for each Category. In order to obtain a single final value representing the total area for each Category, the "Math.Sum" node is used. This node sums all the values inside a list containing integer or double formatted data. These values are then displayed in Dyno, through the use of the "Watch" nodes on the right side of Figure A.18.

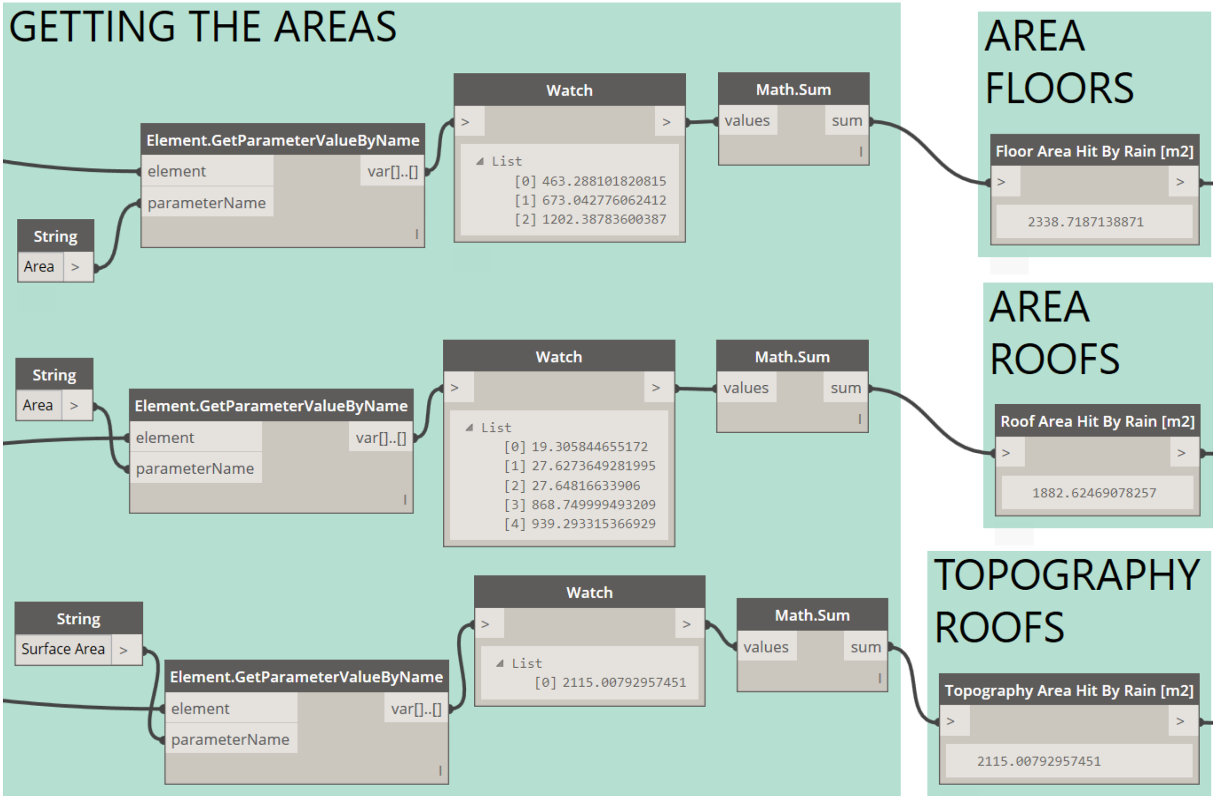

Fig. A.18 – Created Dynamo code for retrieving and displaying all elements areas

A.1.10. Coloring elements on Revit and Dynamo

This next step is done purely with the purpose of better transmitting what the program is doing to the user and the programmer. This way, the first can perceive which elements the program is analyzing and the second can check if the software is actually doing what it is supposed to do. As such, all the topmost topography, floors and roofs areas that were intercepted by the “rain” are colored with three different colors. Obviously, some detail was given to the choice of colors in order to transmit an easy, quick, and intuitive view of the Revit model:

- Topography is colored green, since its normally covered with vegetation;
- Roofs are colored yellow, being the element most exposed to the sun;
- And Floors are colored blue in order to have a good contrast between are three element Categories.

In Figure A.11 it is possible to review this color palette and the evident contrasts they create.

Fig. A.19 – Color palette used

This way, the elements are completely colored in the Dynamo interface for a better understanding of what is going on. However, since coloring the full Revit model might be too intrusive for the user, only the border colors of each element are actually overrided in the Revit model, still offering a good perception of the intercepted elements and also the necessary distinction between the different Categories.

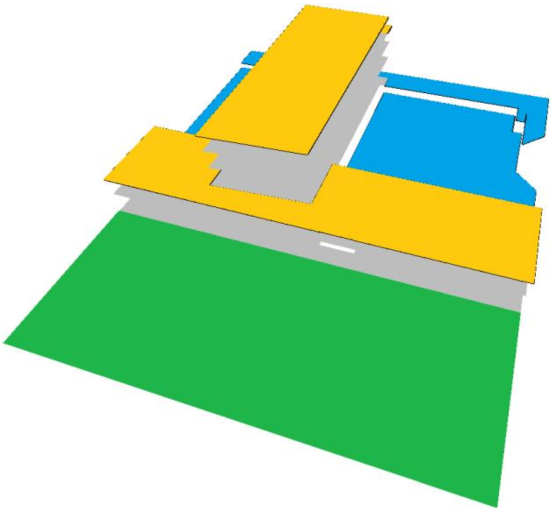

Fig. A.20 – Elements color display inside Dynamo (frontal view)

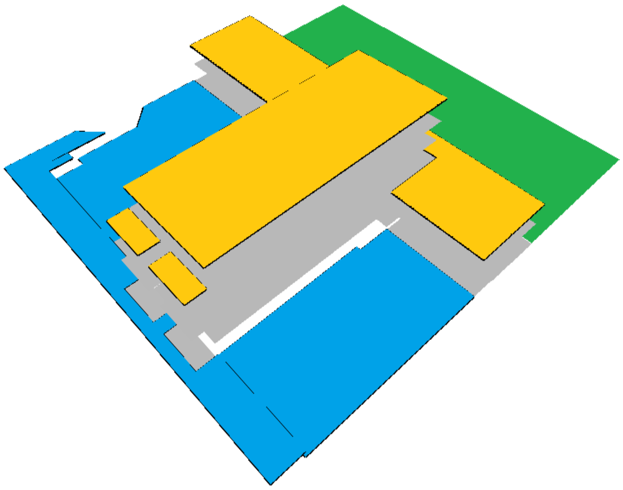

Fig. A.21 – Elements color display inside Dynamo (rear view)

Inside the software the coloring is done in two different processes: one for the Revit model and another for the Dynamo model. In both cases, the only required nodes that were previously created are the "Watch" nodes, seen in the previously step, which contain the Floors, Roofs and Topography elements. Thus, as seen by Figure A.13, when coloring Floors, the "Watch" node containing the Floors is used. The same is applied to Roofs, Topography and their respective "Watch" nodes.

In the case of the Revit model, this process is simply done using the "Element.OverrideColorInView" node which requires two inputs: the selected elements, which color are to be overrided, and the selected color. The elements, as it was already mentioned, are introduced connecting the respective "Watch" node. The colors, are created using the "Color.ByARGB" node which, as the name indicates, creates a node using the ARGB code. In this node there are four inputs, one for each aspect of the ARGB code. The "A", for alpha, is linked to the element opacity and by default is valued "255", which means is 100% full opaque. In opposition, using the value "0" would create a fully transparent element. The other three inputs, "R", "G" and "B", stand for Red, Green and Blue. They work exactly in the same way as the RGB code, adopting values between "0" and "255" depending on the color intensity. The default values for these inputs is "0". To obtain the above colors the following codes were used:

- Green – (255, 51, 255, 51);
- Yellow – (255, 255, 255, 0);
- Blue – (255, 0, 204, 204).

In what concerns the Dynamo model, a few more nodes are used in order to achieve the pretended result. Since the elements in Dynamo are not parametrically created, meaning they do not contain parameters to be adjusted (like in Revit), they cannot be overrided. This way, in order to color the different elements, instead of altering the element parameters, in Dynamo the elements need to be displayed as if that parameter had been changed.

As such, using the retrieved elements from the “Watch” nodes alongside the “Element.Faces” node, the element surfaces are selected. Afterwards, in order to increase the software speed, the collected surfaces are joined using the “PolySurface.ByJoinedSurfaces” node. This way, instead of displaying colors in various surfaces this procedure is reduced to only one polysurface. Acquired the polysurfcae, the “Display.BySurfaceColors” node is used to alter the surfaces color. This node requires two diferent inputs: the polysurface previously created and the desired color. However, in the current version of Dynamo the connection between the “Color.ByARGB” node and the display node is flawed, being currently impossible to attribute colors to Dynamo elements using RGB code. As such, files were created containing the color intended and then introduced in the color input using the “Image.Pixels” node. This node transforms each pixel from the image file imported (visible in Figure A.19) into a line inside a color array. This color array is then used as an input in the display node. The image file is imported using the “File Path”, “File.FromPath” and “Image.ReadFromFile” nodes.

The entire code for coloring can be seen in Figure A.22 applied to the Floors.

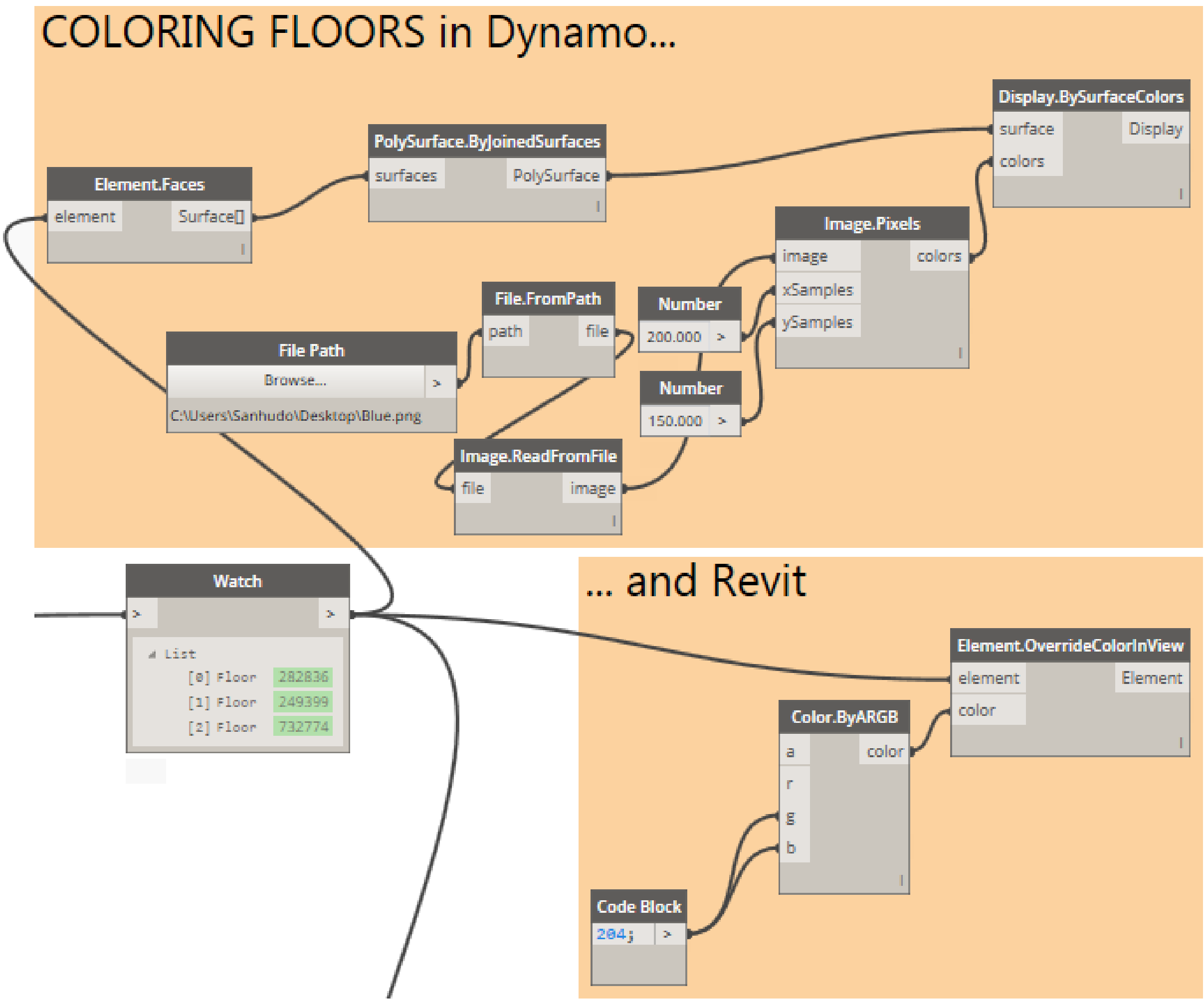

Fig. A.22 – Created Dynamo code for coloring elements

A.1.11. Retrieving Runoff Coefficients and Rainfall Intensity

As seen in 2.7, to obtain the initial runoff of the building site the software needs three pieces of information: the building site area, the runoff coefficient associated to that area, and the rainfall intensity. Until this point, using the connection between Dynamo and the Revit model, the Stormwater Runoff software gathered the required areas, leaving two variables to be acquired. To obtain these variables two methods can be used: the first one, presented in this section, implies the creation of a connection between the proposed software and a database; the second, shown in A.1.12, provides the user the ability to override the values inside the database, allowing for a superior precision and customization associated with the rainfall runoff calculation.

Focusing on the first method, a database must be created containing both these pieces of information: the runoff coefficients and the “a” and “b” coefficients to be used in the Rational Method. To do so, the Extensible Markup Language (XML) was used, not only because of its simplicity, but also because of its interoperability alongside Dynamo. As such, two .xml files were created and connected to Dynamo. These files can be seen in Attachment B.

Regarding the information stored inside these files, the runoff coefficients values were obtained through various studies and researches. In fact, this topic has already been thoroughly studied (Janeiro 2010, Linsley *et al.* 1992, Devine 2012, Thompson 2007, McCuen 1989, Jones Jr 1970, Idowu, Edan, and Damuya 2013, Kuichling 1889, Wilken and de Saneamento Ambiental 1978, Villela and Mattos 1975), thus linking this variable not only to material types but also land uses, soil composition and surface inclination. As such, the found values were summarized in the following table:

Table A.1 – Runoff Coefficients for various land uses

LAND USE	RUNOFF COEFFICIENT	CHOSEN VALUE
Roofs	**0.75 – 0.95**	**0.85**
Business Areas	**0.50 – 0.95**	**0.75**
Downtown areas	0.70 – 0.95	0.85
Neighborhood areas	0.50 – 0.70	0.60
Residencial Areas	**0.25– 0.75**	**0.5**
Single-family	0.30 – 0.50	0.40
Multi-family detached	0.40 – 0.60	0.50
Multi-family attached	0.60 – 0.75	0.70
Suburban	0.25 – 0.40	0.35
Apartment	0.50 – 0.70	0.60
Industrial Areas	**0.50 – 0.90**	**0.7**
Light areas	0.50 – 0.80	0.65
Heavy areas	0.60 – 0.90	0.75
Lawns	**0.05 – 0.35**	**0.20**
Sandy soils	**0.05 – 0.20**	**0.15**
Flat, 2% slopes	0.05 – 0.10	0.08

Average, 2%-7% slopes	0.10 – 0.15	0.13
Steep, 7% slopes	0.15 – 0.20	0.18
Heavy soils	**0.13 – 0.35**	**0.25**
Flat, 2% slopes	0.13 – 0.17	0.15
Average, 2%-7% slopes	0.18 – 0.22	0.20
Steep, 7% slopes	0.25 – 0.35	0.30
Parks, Cemeteries	**0.10 – 0.25**	**0.20**
Playgrouds	**0.20 – 0.35**	**0.30**
Drives and Walks	**0.75 – 0.85**	**0.80**
Streets	**0.70 – 0.95**	**0.85**
Asphalt streets	0.70 – 0.95	0.85
Concrete streets	0.70– 0.95	0.85
Brick streets	0.70– 0.85	0.80
Railroad Yard Areas	**0.20 – 0.40**	**0.30**
Forest	**0.05 – 0.25**	**0.15**
Meadow	**0.10 – 0.50**	**0.3**
Agricultural Land	**0.08 – 0.62**	**0.35**
Bare packed soil	0.20 – 0.60	0.4
Cultivated rows	0.08 – 0.41	0.25
Pasture	0.12 – 0.62	0.37
Unimproved Areas	**0.10 – 0.30**	**0.20**

As seen in Table A.1, each of the various land uses has a determined runoff coefficient interval. To obtain the value used by the software, an average between both extremes is acquired and rounded up to the hundredth decimal place. However, for simplicity, only the grey colored rows from Table A.1 were used on the creation of the Runoff Coefficient .xml file.

For the rainfall intensity, as stated in 2.7, Dynamo obtains the values through equation 2.0 and Table 2.5, both based on the IDF curves. As such, an .xml file was created containing the coefficients from Table 2.5. This file can also be seen in Attachment B.

After creating both .xml files, the database is ready to be used and Dynamo needs to load both files to retrieve their information. This procedure can be seen in Figure A.23 and A.24, respectively for the Runoff Coefficients and the Intensity Coefficients.

The first step in this process, similarly to the image loading method used in A.1.10, uses the “File.Path”, “File.FromPath” and “File.ReadText” nodes to load the .xml file into Dynamo under the string format. A “Watch” node (left bottom corner of Figure A.23 and A.24) is then used to clearly perceive if the file was correctly upload.

After loading these files the “DataSets.DeserializeXML” and “DataSets.GetXMLNode” nodes are utilized to dissect the loaded databases. The first node splits the .xml file into “values” and “nodes”:

"values" contain the actual information inside the database (bottom right "Watch" node in Figure A.23 and A.24); and "nodes" are the parameters used to retrieve this information (bottom middle "Watch" node in Figure A.23 and A.24). As an example, in Figure A.23, by paying attention to the red and orange boxes, it is possible to understand how these "nodes" can be used to retrieve the correspondent "values".

This way, using this information, it is possible to apply the second previously stated XML node to obtain all the "values" inside the .xml file. This node basically uses the retrieved "nodes" to automatically acquire all the correspondent "values". However, instead of calling it "nodes" the term used is "TagName". As such, five "TagNames" are used: "Name" and "RunoffCoefficient", for the Runoff Coefficients.xml file; and "Period", "#a" and "#b", for the Intensity Coefficients.xml file (with the hash being replaced with the pluviometric zone introduced by the user). Using Figure A.23 as an example, it is clear that two separate list are created: one containing all the Land Uses and another containing all the Runoff Coefficients. It should be stressed that both lists are in the same order, thus each Runoff Coefficient index in the second list correctly corresponds to the respective Land Use index in the first list. The same can be seen in Figure A.24 regarding the Return Period and the respective coefficients linked to the chosen pluviometric zone.

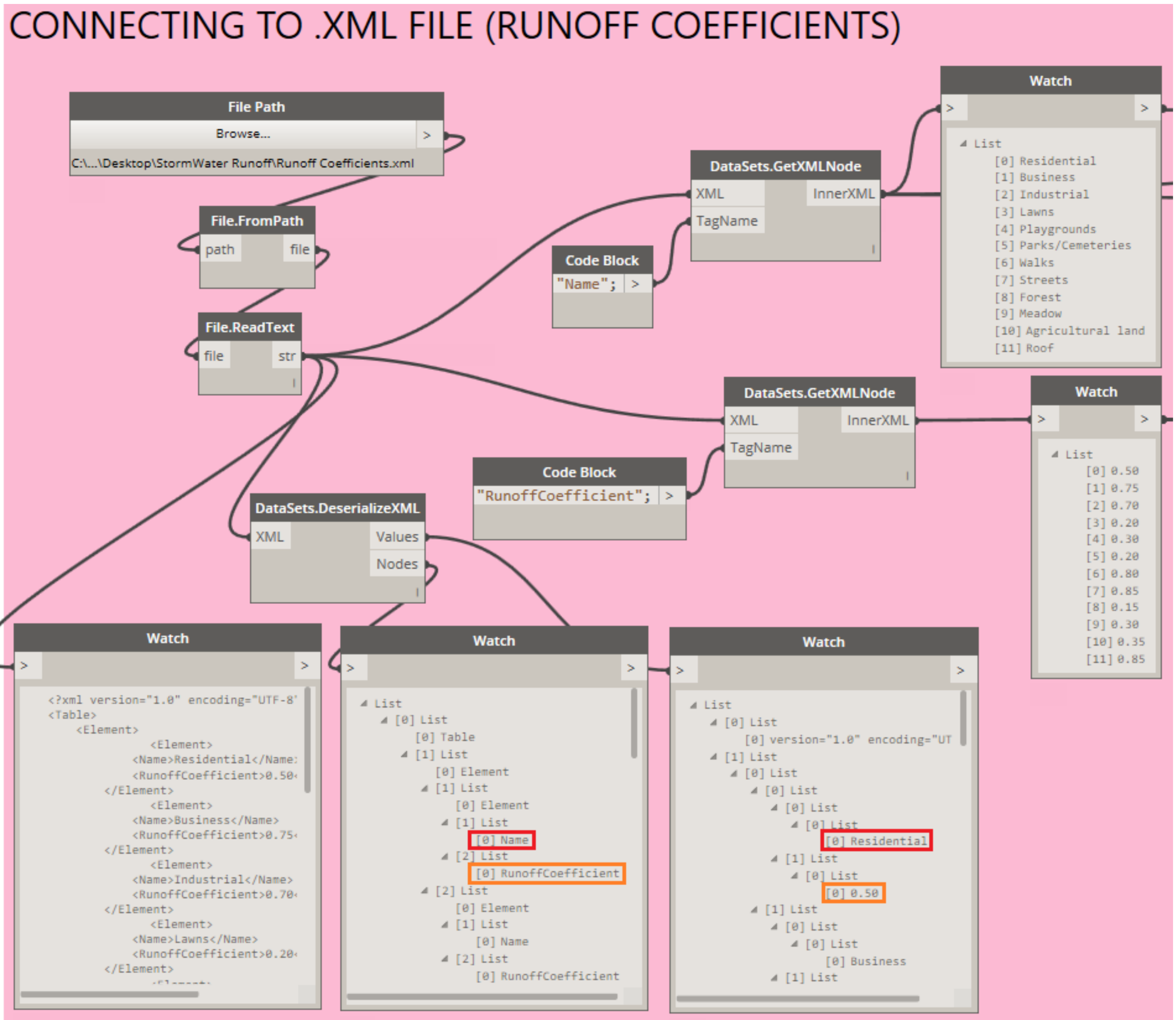

Fig. A.23 – Created Dynamo code for connecting Dynamo with the Runoff Coefficients.xml file

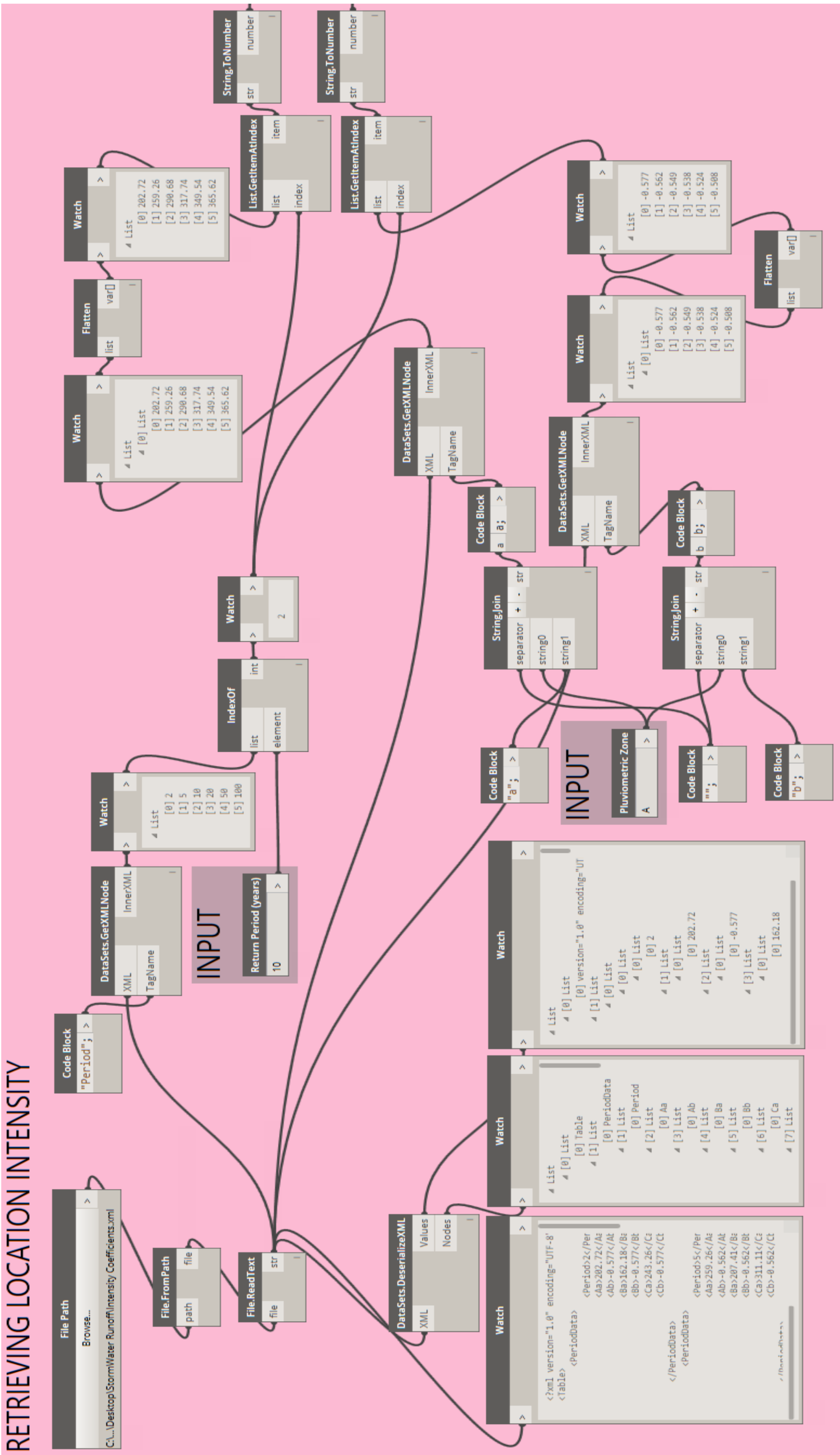

Fig. A.24 – Created Dynamo code for connecting Dynamo with the Intensity Coefficents.xml file

With the database connection properly created, the next step in acquiring this available information is for Dynamo to retrieve the Land Uses, Return Period and Pluviometric Zone inputted by the user. This selection is, once again, done through Dyno and will was thoroughly detailed in 4.5. However, in this section, it is possible to understand how this information is managed inside Dynamo.

As such, the procedure to retrieve information from the database is done four times: three for the roof, floors and topography runoff coefficients and another for the intensity coefficients. All four use roughly the same method:

a) The user inputted information is retrieved from Dyno;
b) The “IndexOf” node is used to retrieve the index associated with the acquired input information from the “nodes” list previously created which, depending on the .xml file, contains the Land Uses or the Return Period. This node basically searches in which index the inputted information equals the data inside a determined list and retrieves that index;
c) The “List.GetItemAtIndex” node is used alongside the index obtained in step 2, in order to retrieve the “value” from the previous created list which, depending on the .xml file, contains the Runoff Coefficients or the Intensity Coefficients values;
d) The values are then converted from string to number to be used in A.1.12.

This procedure can be seen in Figure A.25 for obtaining the Roof Runoff Coefficient. However, since there is only one Land Use associated with the Roof elements (the “Roof” land use), the necessity for the user to input this information is irrelevant. As such, in the case of the Roof Runoff Coefficient, instead of retrieving the input information from Dyno, a “Code Node” containing the string “Roof” is used to acquire the proper index inside the Land Use list.

In Figure A.26 it is possible to see the input nodes replacing the already mentioned “Code Block” node for the Floor and Topography Runoff Coefficients and, in Figure A.24, the input nodes for the Return Period and the Pluviometric Zone can also be seen.

Special attention should be given to the acquisition of the intensity coefficients since, although the process of obtaining these values is roughly the same as the method described above, there are some particularities namely with the acquisition of the pluviometric zone introduced by the user. In fact, this zone has to be joined, through the use of a “String.Join” node, with the letters “a” or “b” to acquire the respective “a” and “b” intensity coefficients from the introduced pluviometric zone. This procedure can be seen in Figure A.24.

In the next section, the second method for obtaining these variables is presented.

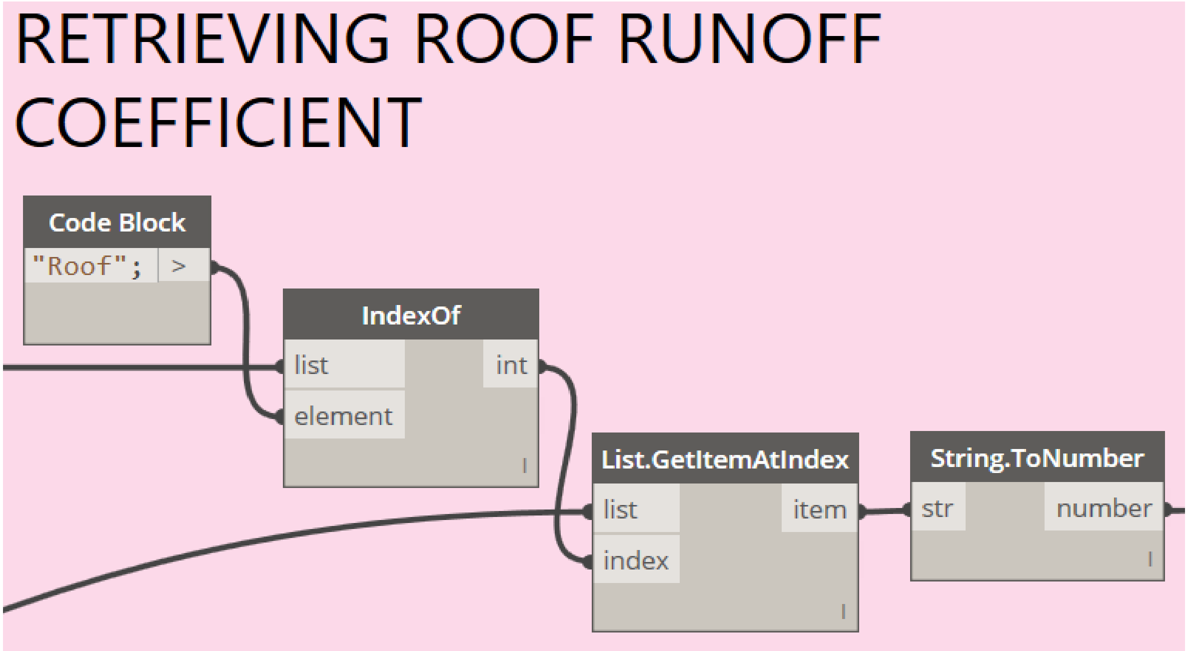

Fig. A.25 – Created Dynamo code for retrieving the desired Roof Runoff Coefficient

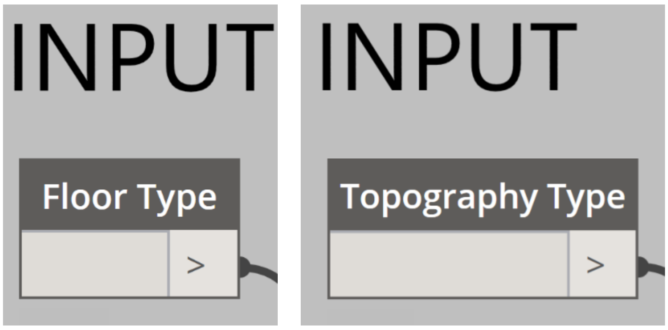

Fig. A.26 – Input nodes used to retrieve the desired Floor and Topography Runoff Coefficients

A.1.12. Override the Retrieving Runoff Coefficients and Rainfall Intensity

As mentioned before in 4.1, the Stormwater Runoff software can also be used as an accurate tool for measuring the rainfall runoff of a building site. However, in order to successfully achieve this objective, the program preset values must be overrided so that the user can input the exact runoff coefficients and rainfall intensity values.

To do this, two necessary inputs must be entered through Dyno. The first is a "Boolean" node asking the user if he wants to override the preset values; the second is a "Number" or "String" node to be filled with the desired override value.

The first step in this process is to check if the Boolean input is true or false. This is done by using the "List.FilterByBoolMask" node. As seen in Figure A.27 and A.28, if the Boolean input is true the entered value is placed in the "in" output port of this node (seen as the index [0] in the node preview of Figure A.27), while if it is false the value is placed in the "out" output port (seen as the index [1] in the node preview of Figure 4.28). After this first step, a list is created containing the override value on index [0], and the preset value, retrieved from the database and previously seen in A.1.11, on index [1]. This order will be most important for the next step. It should be stressed that the "in" port of the "List.FilterByBoolMask" node is the one always linked to this new list and not the "out" port. This way, if the "Boolean" is set to true, the "in" port will contain the desired override value which will be placed in the index [0] of the new list or, in the opposite case, if the "Boolean" node is set to false, the port will be empty, meaning the first index of the new list will also be empty. As such, by using the "Manage.RemoveNulls" node, the empty index [0] is replaced with index [1], containing the preset value. This way, in either case the wanted value will always be in index [0].

Once this information is correctly managed, it is possible to retrieve the desired information inside index [0] after flattening the list, sequentially sending it to A.1.13. Although Figures A.27 and A.28 are for Floors, the exact same procedure is done for Roofs, Topography and the Rainfall Intensity.

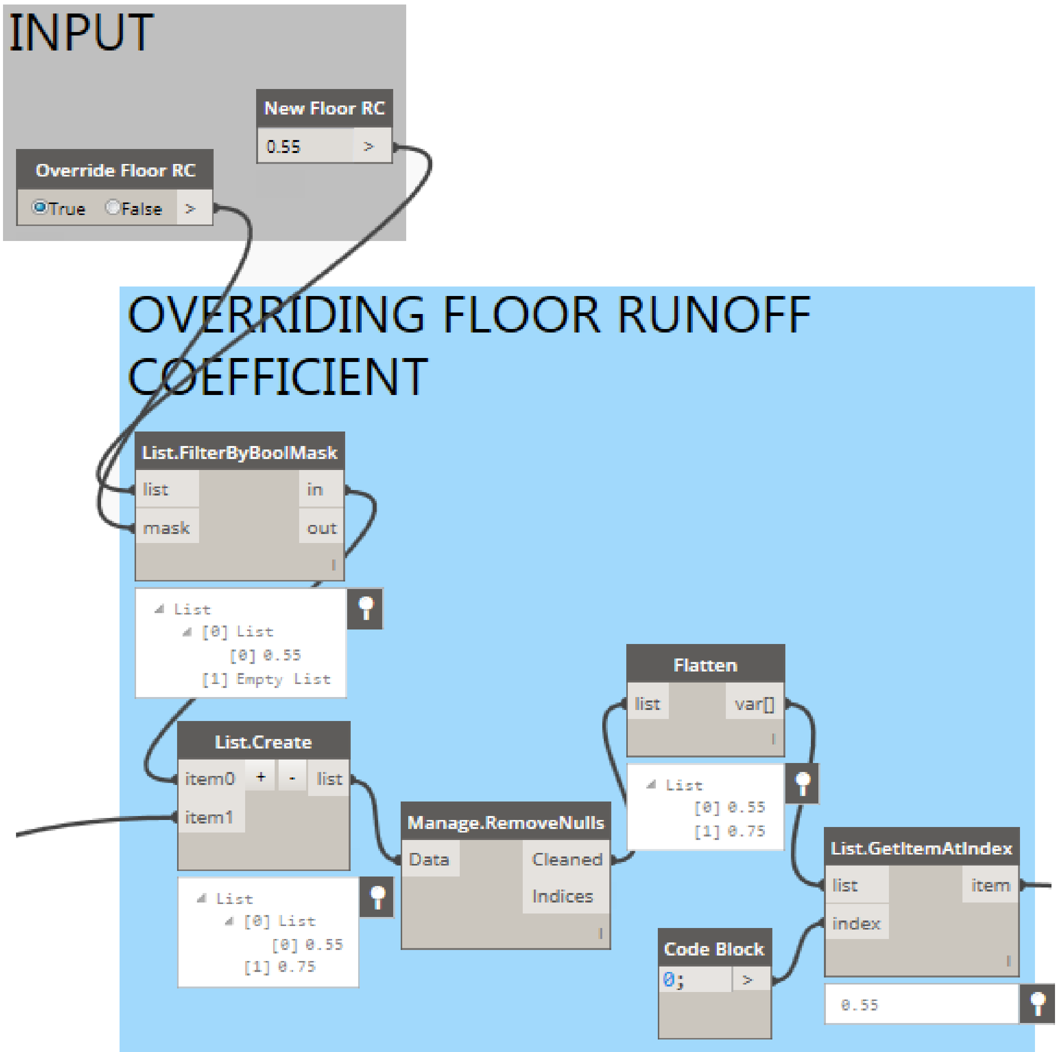

Fig. A.27 – Created Dynamo code for overriding elements. Example showing the case of overriding the values

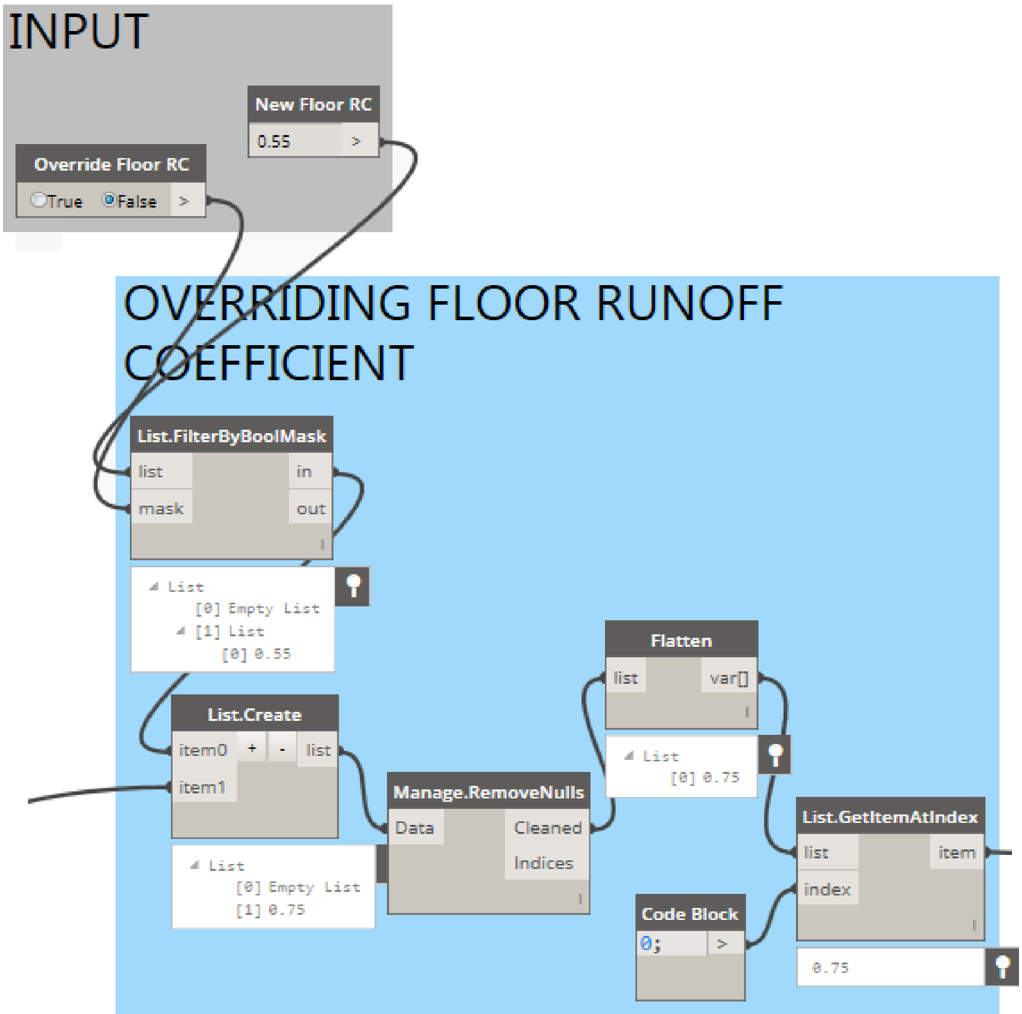

Fig. A.28 – Created Dynamo code for overriding elements. Example showing the case of not overriding the values

A.1.13. Obtaining the Initial Rainfall Runoff

Finally, the last step in acquiring the initial runoff is to apply the average maximum rainfall intensity and the Rational Formula equations seen in 2.7. As such, Dynamo has to replicate a sequence of mathematical operations that can be seen through Figures A.29, A.30 and A.31.

In Figure A.29, it is possible to see the last input the user has to introduce in Dyno: the Storm Duration, in minutes. This input is then changed from a string format to number, through the "String.ToNumber" node and powered by "b" (which was obtained in the last section) through the "Pow" node, entitled "Duration ^ b" for better understanding. The acquired result is then multiplied by "a", which was also obtained in the last section, and 0.001 to obtain the rainfall intensity in meters per hour.

In Figure A.30, a simple "Multiplication" node is used to multiply each element area for the correspondent runoff coefficient. The resulted values are then joined in a list, using the "List.Create" node and summed using the "Math.Sum" node, in order to obtain the sum of all the previous results. The acquired value is then multiplied by the rainfall intensity in Figure A.31, which was obtained in the last section after the override code is run, resulting in the acquisition of the initial runoff flow in cubic meters per hour. This flow is then converted in liters per hour, by multiplying it by a thousand. The last step is to multiply the resulting flow by the duration of the storm (which was converted to hours by multiplying it by one over sixty), obtaining the total precipitation volume in liter, which is sent to Dyno using a "Watch" node.

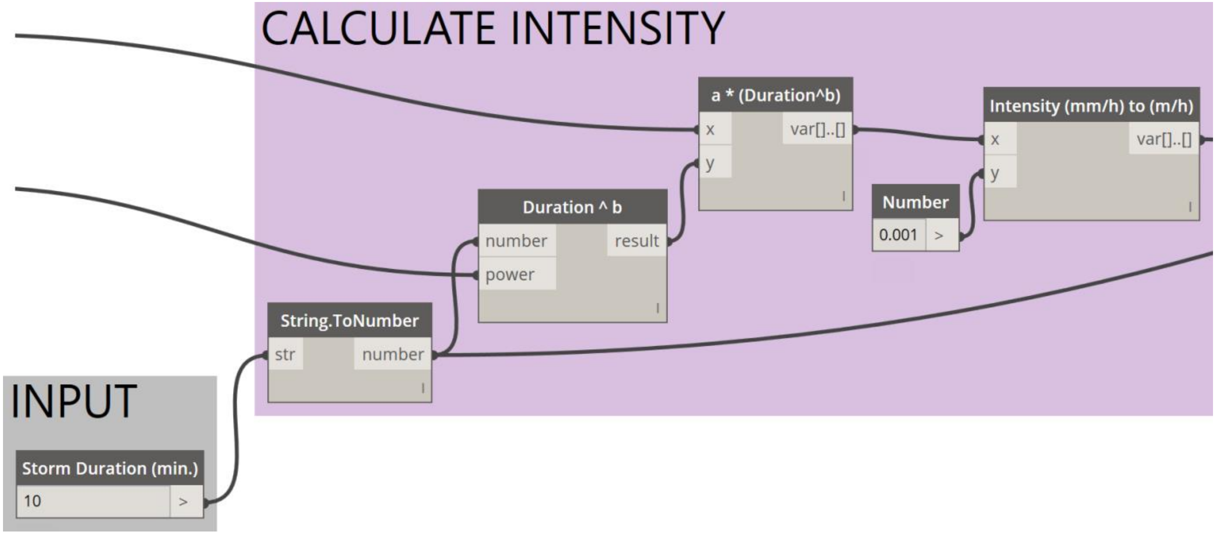

Fig. A.29 – Created Dynamo code to calculate the storm intensity

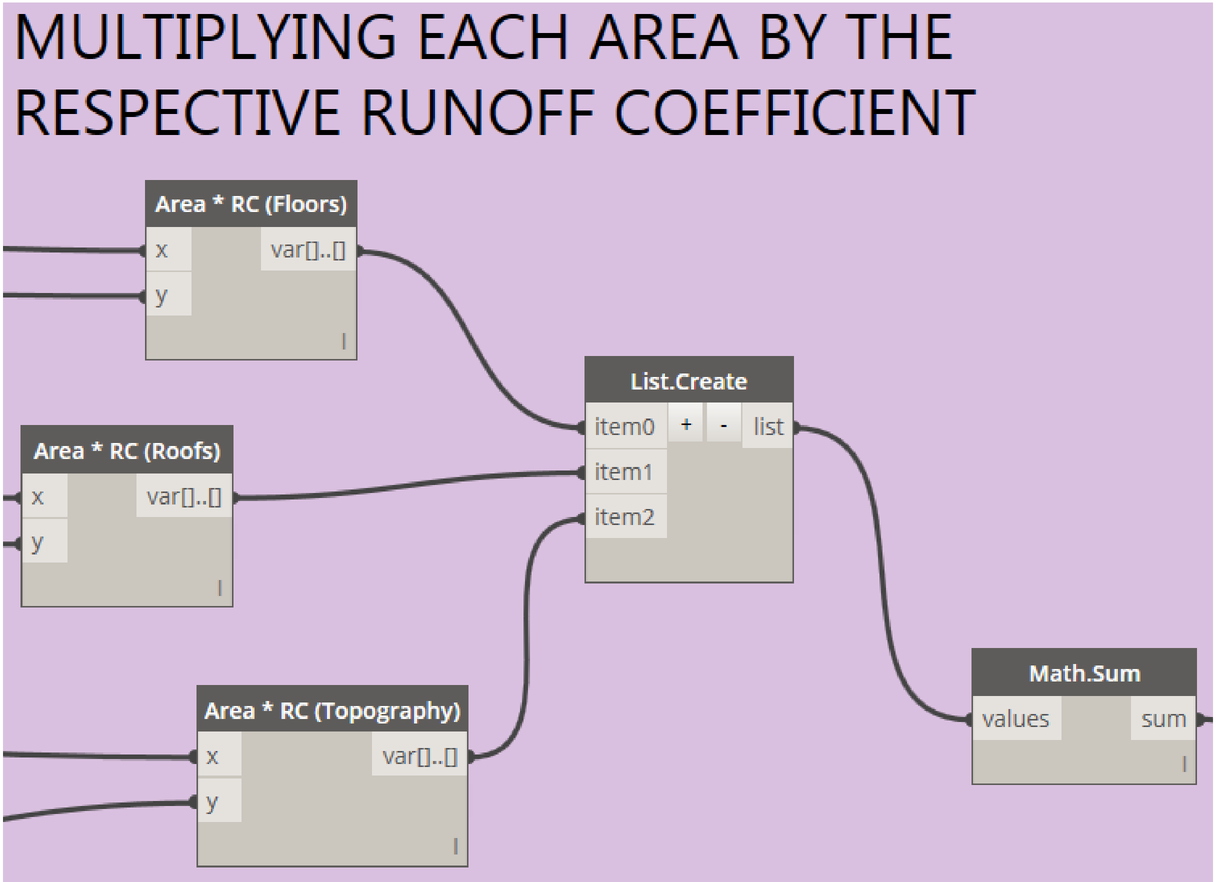

Fig. A.30 – Created Dynamo code for multiplying element areas for the respective runoff coefficient inside Dynamo

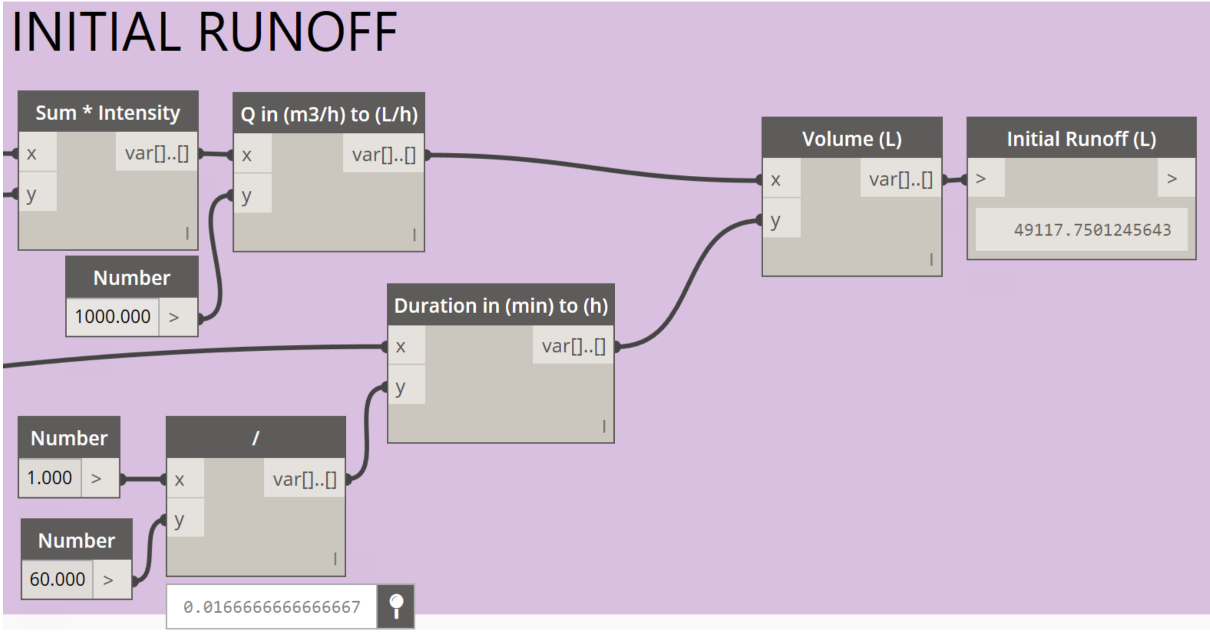

Fig. A.31 – Created Dynamo code to obtain the initial runoff inside Dynamo

A.2. APPLYING LID-BMP TO REDUCE THE INITIAL RUNOFF

A.2.1. OBTAINING THE RAINFALL RUNOFF TO ELIMINATE

The first step in obtaining the required LID-BMP for correcting the initial runoff is to actually determine which amount of runoff should be eliminated. To do so, as explained before, there are two possible ways: choose a LEED credit to pursue or indicate the desired final runoff.

In Figure A.32, two lists are created with the purpose of computing this first way. The first list, contains all the possible LEED credits to be achieved with this software, and the second contains the necessary percentage of runoff to keep after the mitigation is completed. Obviously, both list are in the same order, with the percentages in the second list corresponding to the credits in the first one. As such, using the user input, the index of the chosen credit is retrieved using the "IndexOf" node, to be used alongside the "List.GetItemAtIndex" node in obtaining the corresponding percentage. This percentage is then multiplied by the introduced initial runoff, obtained from the first half of the software, to acquire the final runoff volume.

However, after acquiring this final runoff, the software checks if the user actually wants to pursue a determined LEED credit or an inputted final runoff. If it is confirmed that the user actually desires to achieve a pre-determined final runoff volume, the value acquired in the last paragraph is replaced with the one the user introduced. To do this, the exact same procedure used in A.1.12 is applied to "override" or not "override" the value acquired. This procedure can be seen in Figure A.33. Nevertheless, the final obtained value, being either the one acquired from the LEED credits or the one directly introduced by the user, is subtracted to the initial runoff using the subtract node seen in Figure A.34, resulting in the acquirement of the necessary volume to be mitigated by the LID-BMP.

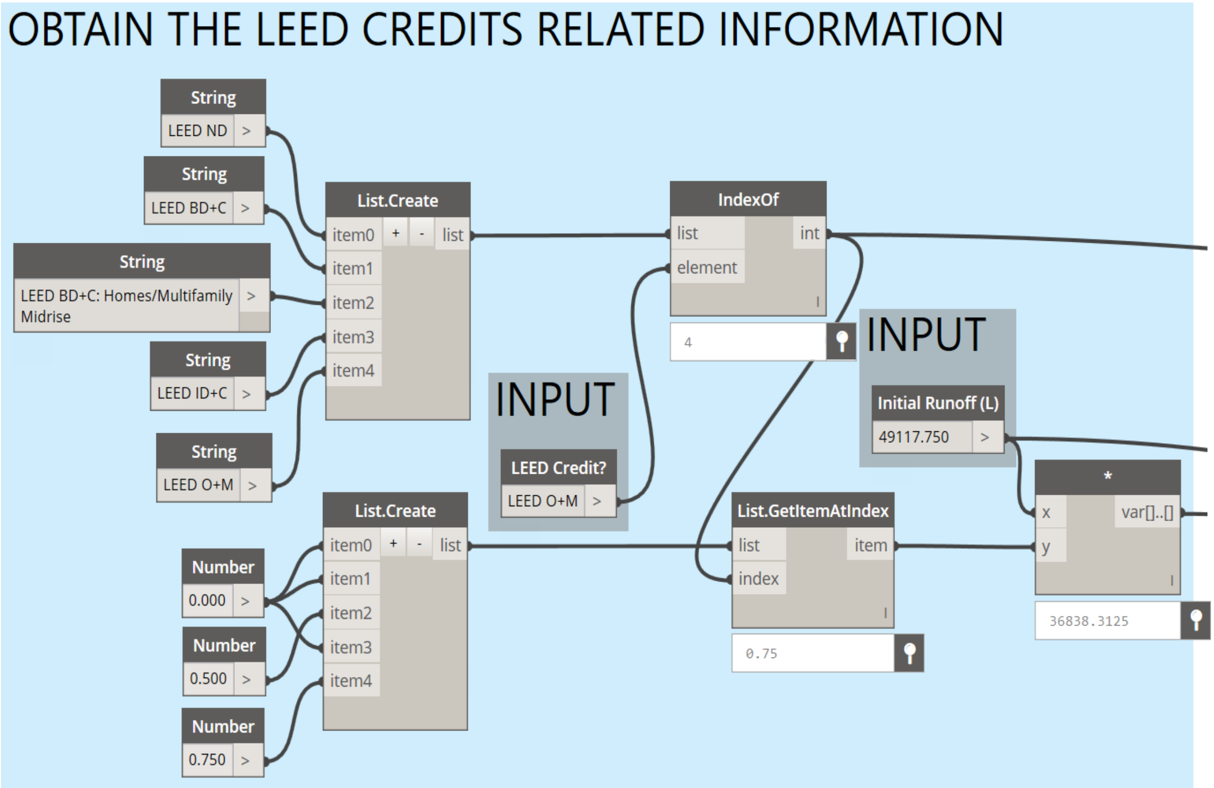

Fig. A.32 – Created Dynamo code to acquire the final runoff volume if the user chooses a LEED credit

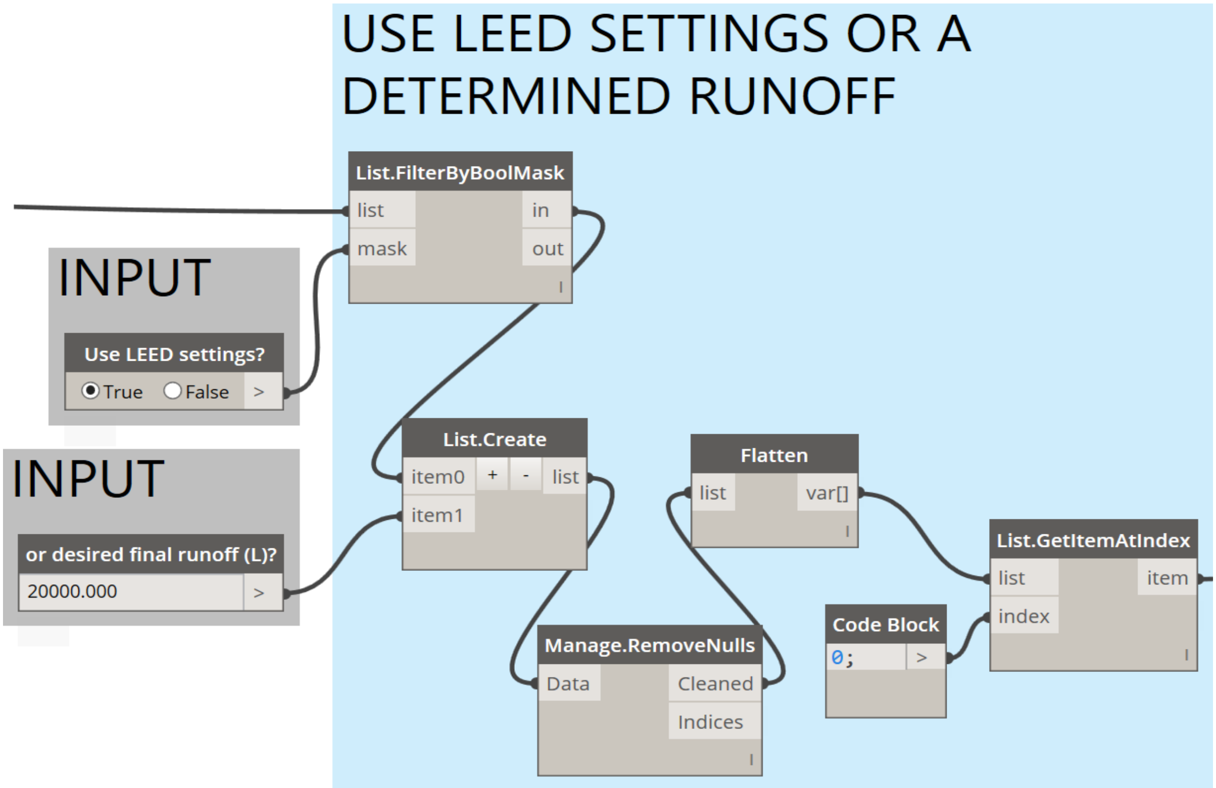

Fig. A.33 – Created Dynamo code to verify if the user is trying to pursue a LEED credit or achieve a pre-determined final runoff

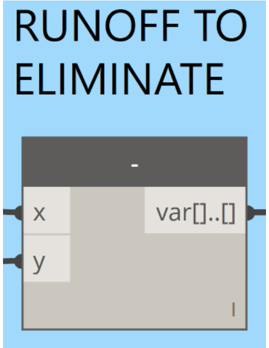

Fig. A.34 – Acquire the total runoff to be mitigated by the LID-BMP

A.2.2. Resolve the LEED BC+C: Homes/Multifamily Midrise credit

From all the possible credits to be obtained using the designed software one set of credits has completely different requirements to be obtained. In fact, although most runoff related credits demand a certain percentage of runoff to be eliminated, the "LEED BC+C: Homes/Multifamily Midrise" credit requires a certain ratio between permeable and impermeable areas. In fact, as seen in Figure A.36, this credit offers the possibility to obtain three credit points: one if the permeable area has a percentage of 50 to 65%; two for a percentage between 65 and 80%; and three if the permeable area comprises more than 80% of the total area.

Since this credit is completely different from the remaining credits, it is computed separately and, in the end of the software run, the program checks if the introduced credit equals this one and chooses the displayed information accordingly. The actual verification is done through the use of a simple "Equal" node in the bottom of Figure A.36, which validates if the chosen credit equals the one in index "2" or, in other words, the "LEED BC+C: Homes/Multifamily Midrise" credit.

Also, since this credit requires the building permeable and impermeable areas, in Figure A.35 the acquired areas from the first half of the software are retrieved from Dyno and linked to the nodes in Figure A.36. The Topography Area is considered permeable while the Roof and Floor areas are considered impermeable. The actual credit validation is done throughout a series of "If" nodes, as seen in Figure A.36, which compare the obtained ratio with the credit requirements.

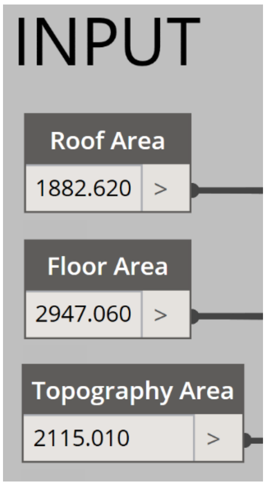

Fig. A.35 – Areas obtained from the first half of the software

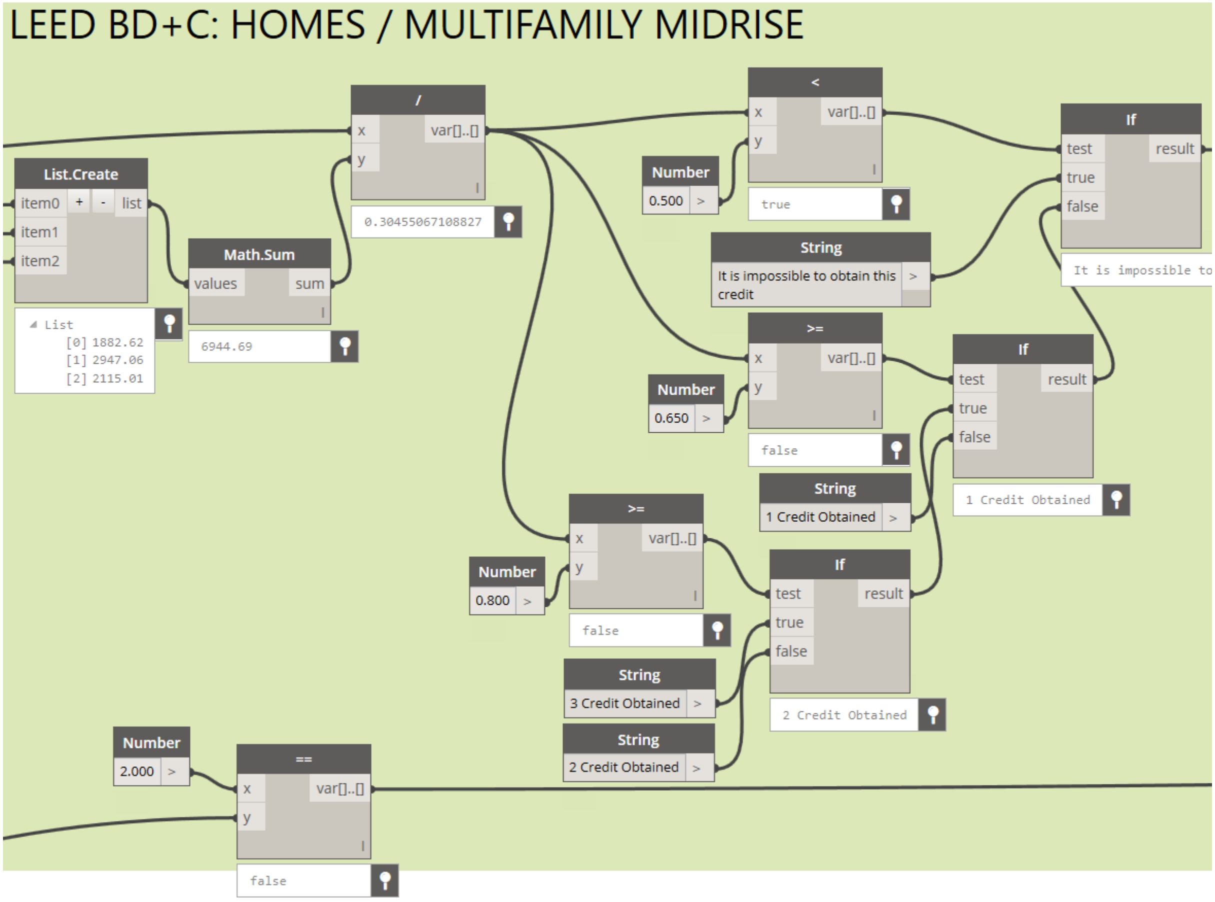

Fig. A.36 – Created Dynamo code to compute the LEED BC+C: Homes/Multifamily Midrise credit

A.2.3. Retrieve the information from the LID-BMP database

Focusing on the remaining credits, to be able to eliminate the runoff obtained from Figure A.34, the information regarding the available LID-BMP has to be acquired by the software for further analyze. As such, the exact same process seen in section A.1.11 is used to connect the software to the created database, and then extract the information stored in it. This procedure can be seen in Figures A.37, A.38, A.39 and A.40 for the connection and extraction of information from the BMP.xml file, which can be seen in Attachment B.

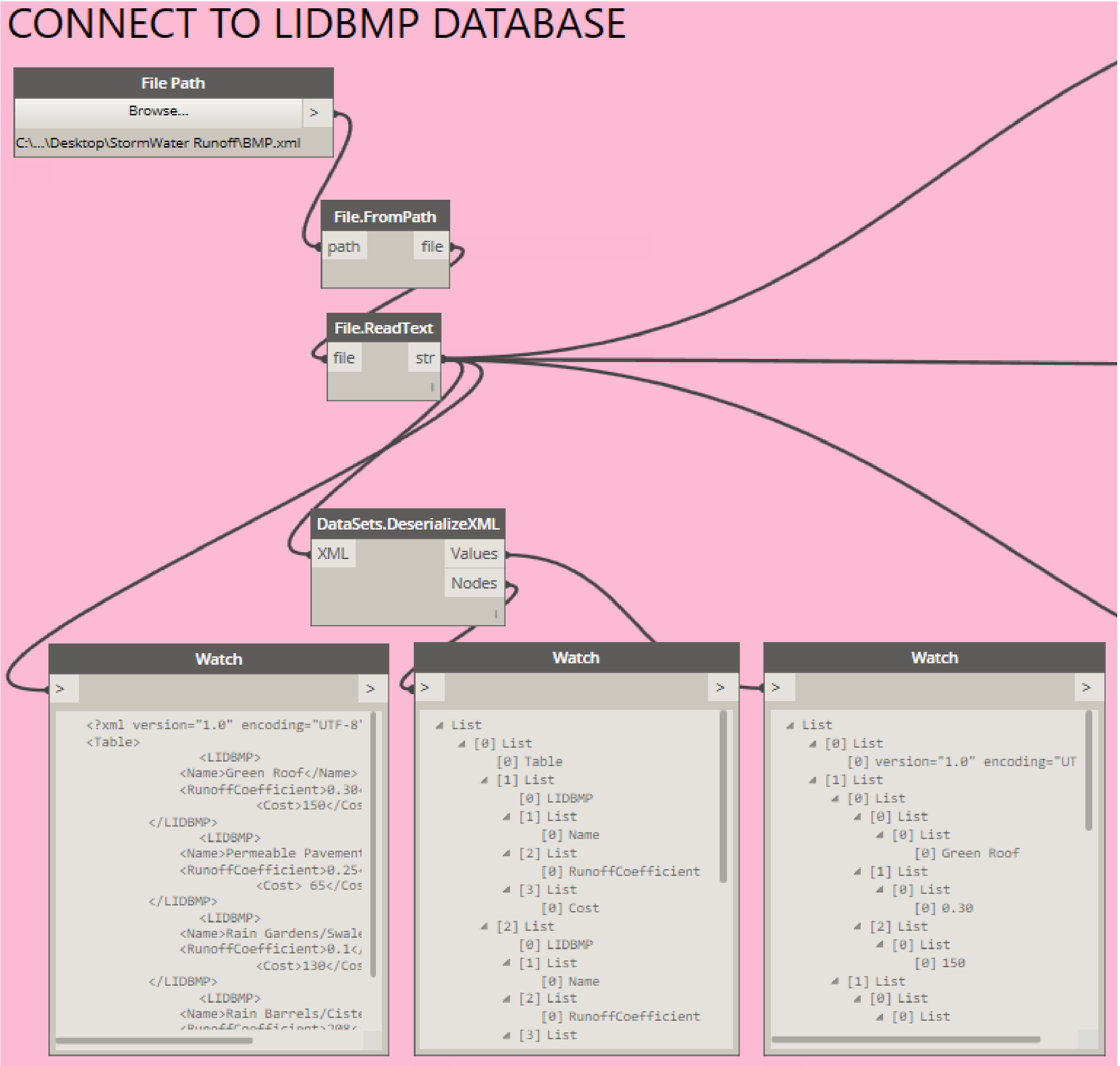

Fig. A.37 – Created Dynamo code to connect Dynamo to the BMP.xml file

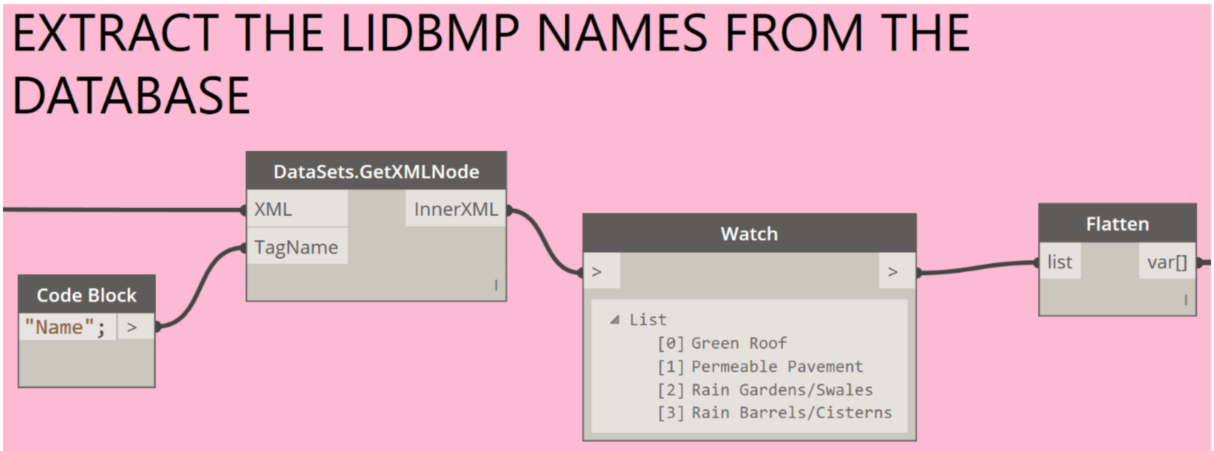

Fig. A.38 – Created Dynamo code for extracting the LID-BMP names from the database

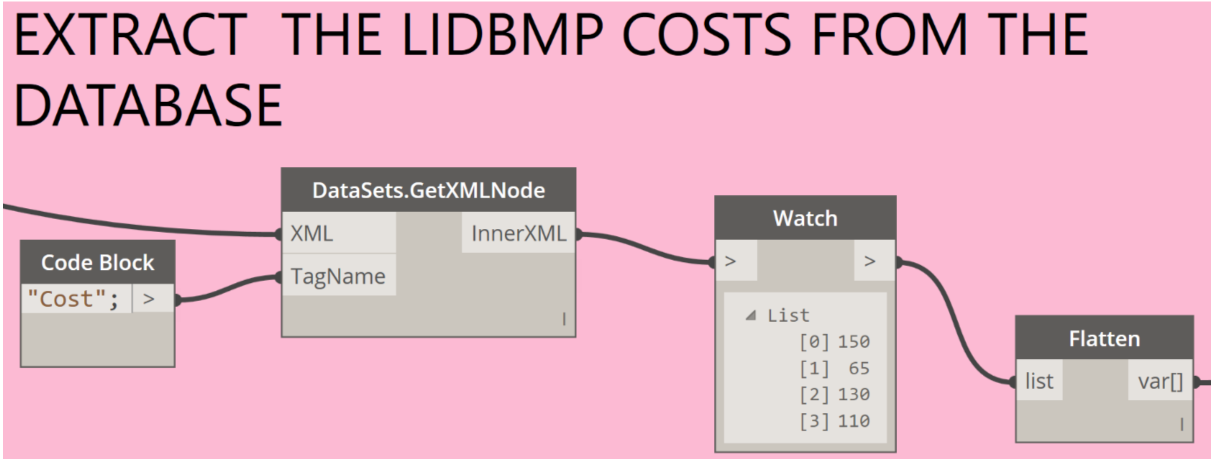

Fig. A.39 – Created Dynamo code for extracting the LID-BMP costs per square meter or unit from the database

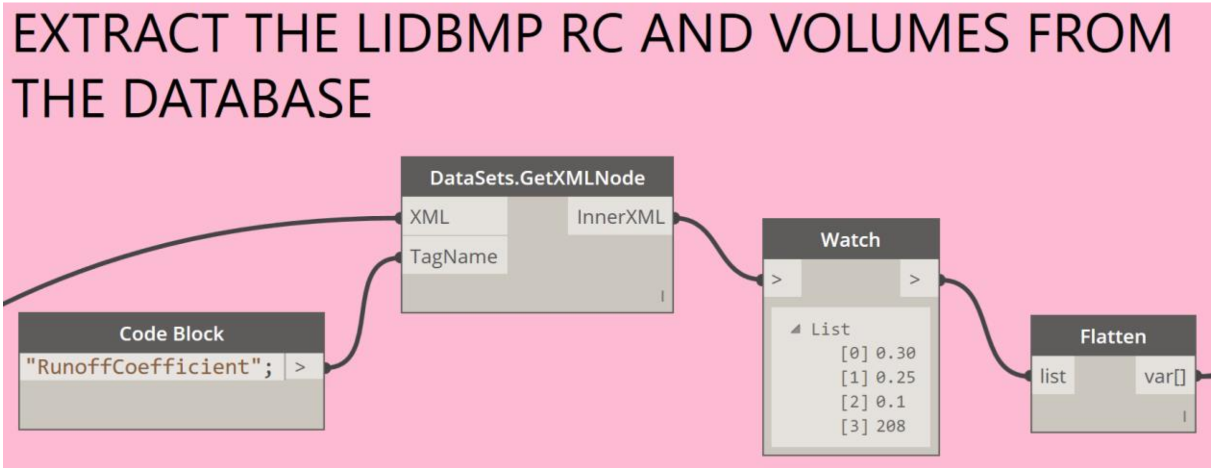

Fig. A.40 – Created Dynamo code for extracting the LID-BMP respective runoff coefficients and storage volumes from the database

A.2.4. MANAGE THE EXTRACTED RUNOFF COEFFICIENTS

Retrieved the information inside the database, the next step is to actually manipulate and use that information. As such, regarding the LID-BMP names and costs nothing has to be changed since they will only be applied later in the software. However, to obtain the volume mitigated by the implementation of LID-BMP, the corresponding runoff coefficients have to be subtracted to the Category runoff coefficients used in the first half of the software. This is done to obtain the difference between these runoff coefficients or, in other words, the coefficient that results on acquiring the mitigated runoff volume.

Also, a quick explanation should be given regarding the runoff coefficients and volumes retrieved from this list. In the most part, all the displayed values were directly obtained from averages encountered on the studied researches seen in section 2.6. For example the runoff coefficient for Green Roofs is 0.3, for Permeable Pavement is 0.25 and the volume for Rain Barrels is 208 liters. However, regarding the Rain Gardens/Swales, an exact value for its runoff coefficient was not encountered. Despite this, carefully analyzing the displayed information in section 2.6.3.4, it is possible to realize that the amount of runoff typically mitigated by this LID-BMP ranges from 40 to 99%. Yet, by further examining the stated researches, it is also possible to understand that the 40% value is actually an outlier value obtained from a consecutive occurrence of large intensive storms. As such, by eliminating this occurrence, the average runoff elimination ranges from approximately 80 to 99%. This range is further confirmed by the runoff coefficient typically seen for lawns (which one could say are inferior versions of rain gardens/swales) which is 0.2 or, in other words, a mitigation of 80%. This way, it is possible to conclude that the runoff coefficient for rain gardens/swales would typically vary between 0.2 and 0.0, resulting in a mean value of 0.1.

Continuing the information manipulation, in Figure A.41 this process is conducted by first splitting the retrieved runoff coefficients and volumes into separate lists using the “List.Deconstruct” node, which retrieves the first item on the list thus creating two separate lists. By using this node four times the list is completely split. Afterwards, the single index lists are converted into numbers and subtracted to the respective Category runoff coefficients that were used in the first half of the software. As seen in Figure A.41, these initial runoff coefficients are introduced by the user. It should be noted, that this process is only done for the runoff coefficients, which means the Rain Barrels/Cisterns storage volume stays unchanged. Afterwards, the resulting differences between the runoff coefficients replace the corresponding values inside the list retrieved from the database, by applying four “List.ReplaceItemAtIndex” nodes alongside four “Number” nodes.

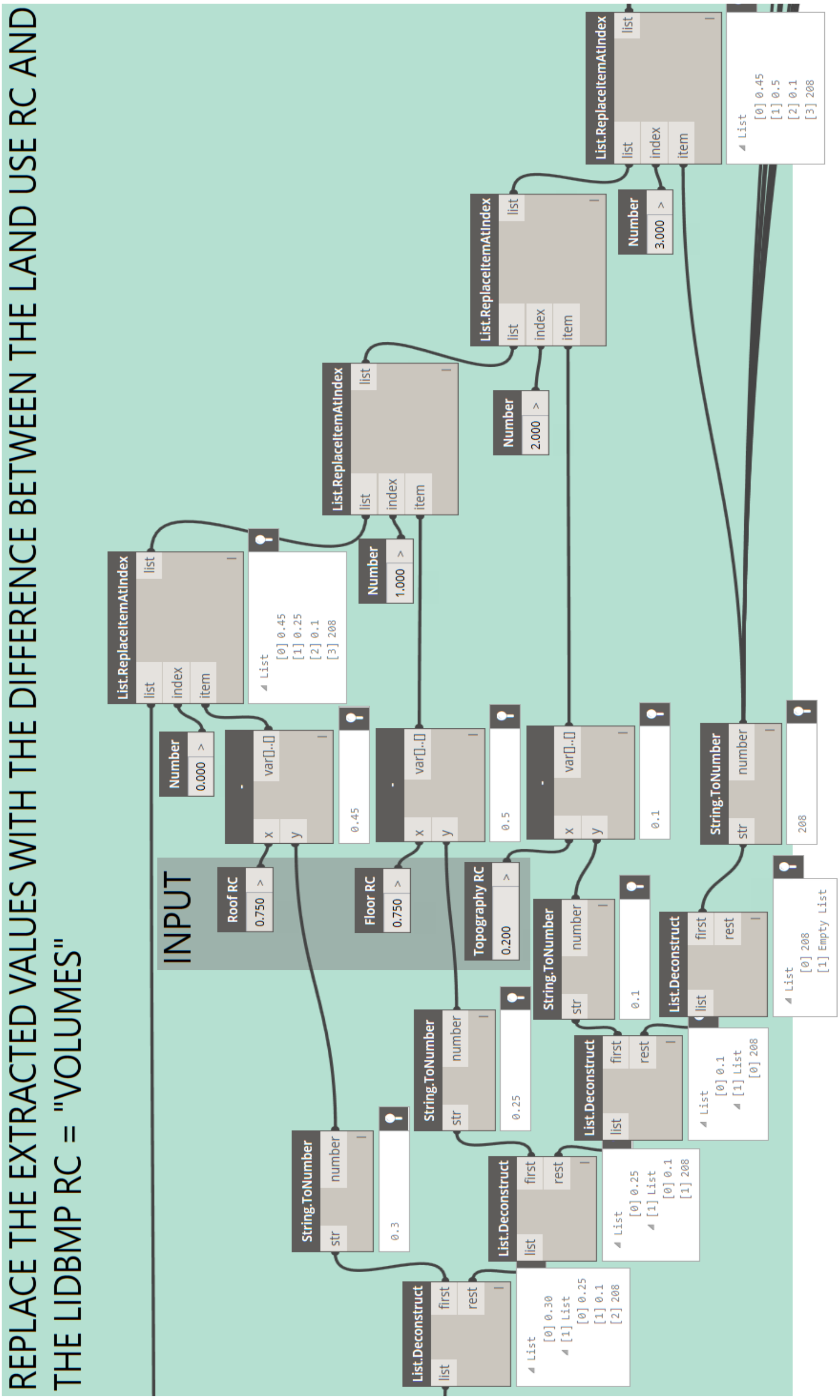

Fig. A.41 – Created Dynamo code to obtain the difference between the Category runoff coefficients and the LID-BMP runoff coefficients

A.2.5. Acquire the introduced LID-BMP indexes

Organized all the LID-BMP information is time to actually retrieve the LID-BMP chosen by the user. As such, in Figure A.42, the three LID-BMP introduced by the user (Rain Barrels/Cisterns, Green Roofs, and Permeable Pavement), are obtained by the software through the text nodes linked to Dyno. This nodes are then connected to the “List.Create” node in Figure A.43 which creates a list in the exact same order the LID-BMP were introduced. This order will be most important in case the “priority order” option is selected. After creating this list, the “Strings.SearchListForString” node obtains the indexes of the empty rows and removes them with the “List.RemoveItemAtIndex” node. This is done in order to prevent errors in the software’s long run. To guarantee the empty rows were eliminated, a “List Not Empty” node is used alongside the “List.Map” node to create a function and retrieve the new list (only containing the selected LID-BMP), from the “in” port of the “List.FilterByBoolMask” node.

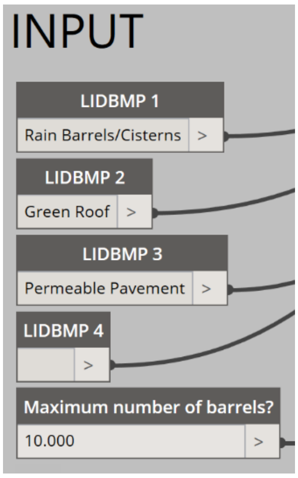

Fig. A.42 – Input nodes to acquire the selected LID-BMP and the maximum number of Rain Barrels/Cisterns

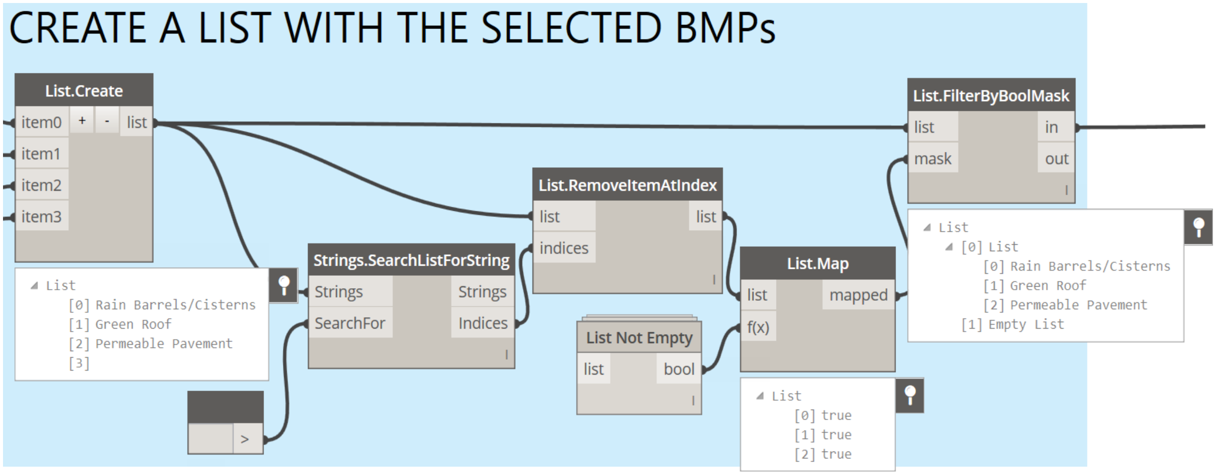

Fig. A.43 – Created Dynamo code to obtain the introduced LID-BMP

This list in then deconstructed using the same process applied in the last section, in order to obtain the respective indexes (from the database list) for each of the selected LID-BMP. This process can be seen in Figures A.44 and A.45. For instance, by analyzing Figure A.42, it is possible to conclude that the first selected LID-BMP is the Rain Barrels/Cisterns and thus in Figure A.43 final list it should occupy the [0] index, which it does. On the other hand, it also means that in Figure A.44 this LID-BMP should be the first to be separated and that in Figure A.45 the topmost "IndexOf" node should retrieve the Rain Barrels/Cistern index from the database list. By analyzing the Figure A.38 it is possible to conclude that the corresponding index for the Rain Barrels/Cisterns is index [3], which corresponds to the index displayed in Figure A.45, thus the software is performing correctly. It should also be pointed that the last index in Figure A.45 is "-1" since in this example the user only introduced three LID-BMP which meant there were only three indexes to be retrieved.

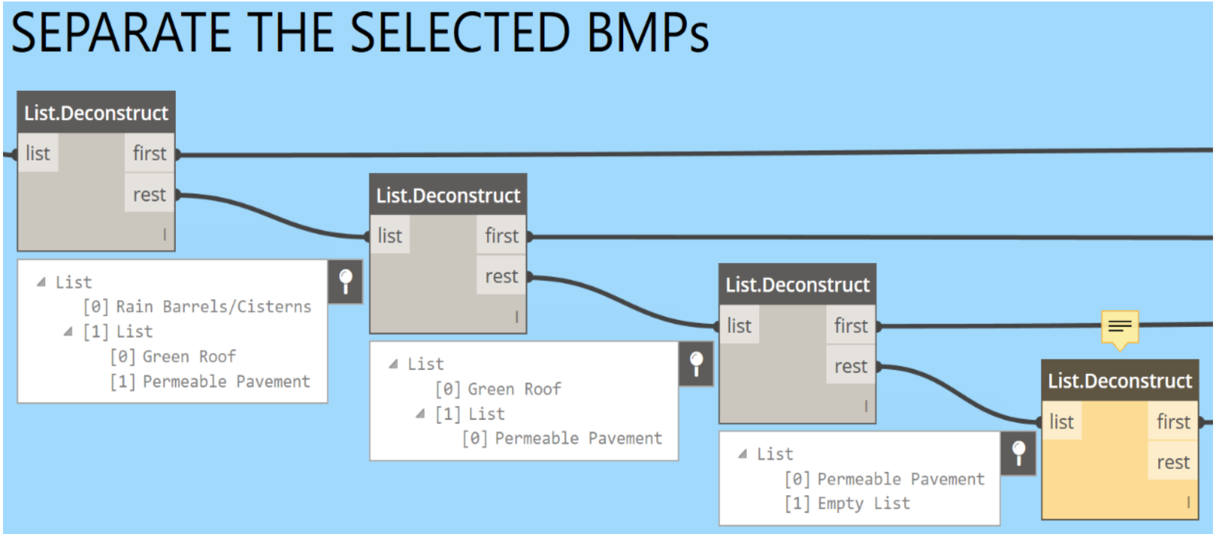

Fig. A.44 – Created Dynamo code to separate the introduced LID-BMP

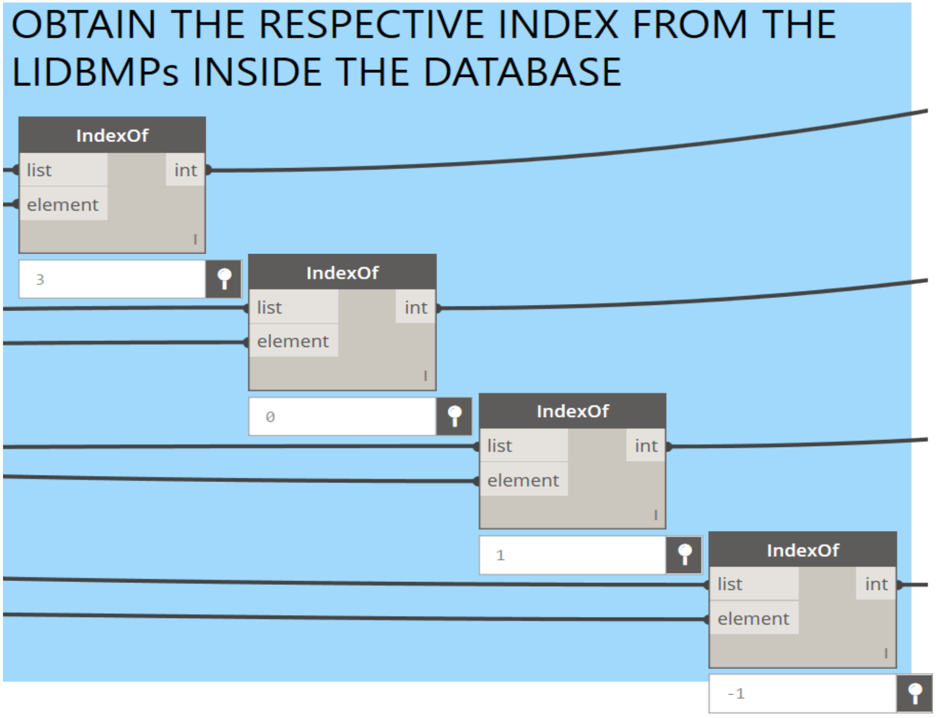

Fig. A.45 – Created Dynamo code to retrieve the database corresponding indexes for the introduced LID-BMP

A.2.6. VERIFY WHICH PRIORITIES WERE INTRODUCED BY THE USER AND RETRIEVE THE CORRESPONDENT INFORMATION

Acquired the LID-BMP and their respective indexes the software checks which priorities the user introduced. As such, in Figure A.46 it is possible to see the input boolean nodes the user has to fill in Dyno to correctly run the software. There are three possible priorities: the order in which the user introduces the LID-BMP; the solution that requires the minimum area; and the solution that requires the minimum cost. In this case, the user selected the order and the cost as priorities for the obtained solution. However, as it will be possible to understand, since the priority order directly conflicts with the minimum cost, the priority order will be the deciding factor.

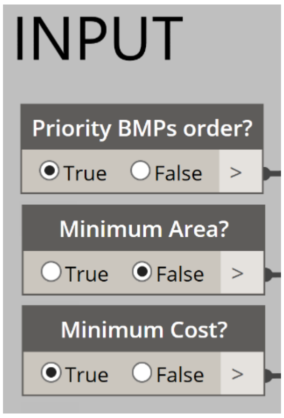

Fig. A.46 – Input nodes used to acquire the selected priorities for the solution

With the priorities obtained the software retrieves the correspondent information from the database. This means if the cost priority is selected, the software retrieves the LID-BMP costs or, if the area priority is selected, the software retrieves the runoff coefficients. Since the order priority overrides the previous two priorities, it will be accounted for later on, in section A.2.8. As seen in Figure A.47, another series of "If" nodes is used to acquire the selected priority information. The first two "If" nodes (far left side of Figure A.47) are linked to the "Minimum Area?" and the "Minimum Cost?" input nodes, respectively the upper and lower "If" nodes. Depending on which priority is selected, a list is created containing the number "0" and the number "1" or "2": the number "1" means the minimum area priority is selected while the number "2" means the minimum cost priority is selected. Since in this example the user selected the cost priority, the obtained list contains the number "0" and the number "2". Afterwards, two "ListContainItem" nodes are used to check which number the list contains (number "1" or number "2") and a boolean list is created with the true value on the first or second index depending on the selected priority. This is done by using an "IndexOf" node alongside an "Equal" node and a "Number" node containing the number "1". This means if the true value is in the "second" index (which means the number "2" was on the list) the "Equal" node will contain the value "True" and retrieve the information regarding the LID-BMP costs. However, if the list contained the number "1", the true value would be on the "first" index, which meant the "Equal" node would contain the value "False" and retrieve the runoff coefficients for the LID-BMP.

Finally, a "CountTrue" node (which counts the number of true values in a list) is used to check if the user did not select any of the priorities (zero trues) or if he selected both (two trues). As such, if the count is different than one, the software display an "Error". Otherwise, the information retrieved in the last paragraph is normally sent to the nodes in Figure A.48.

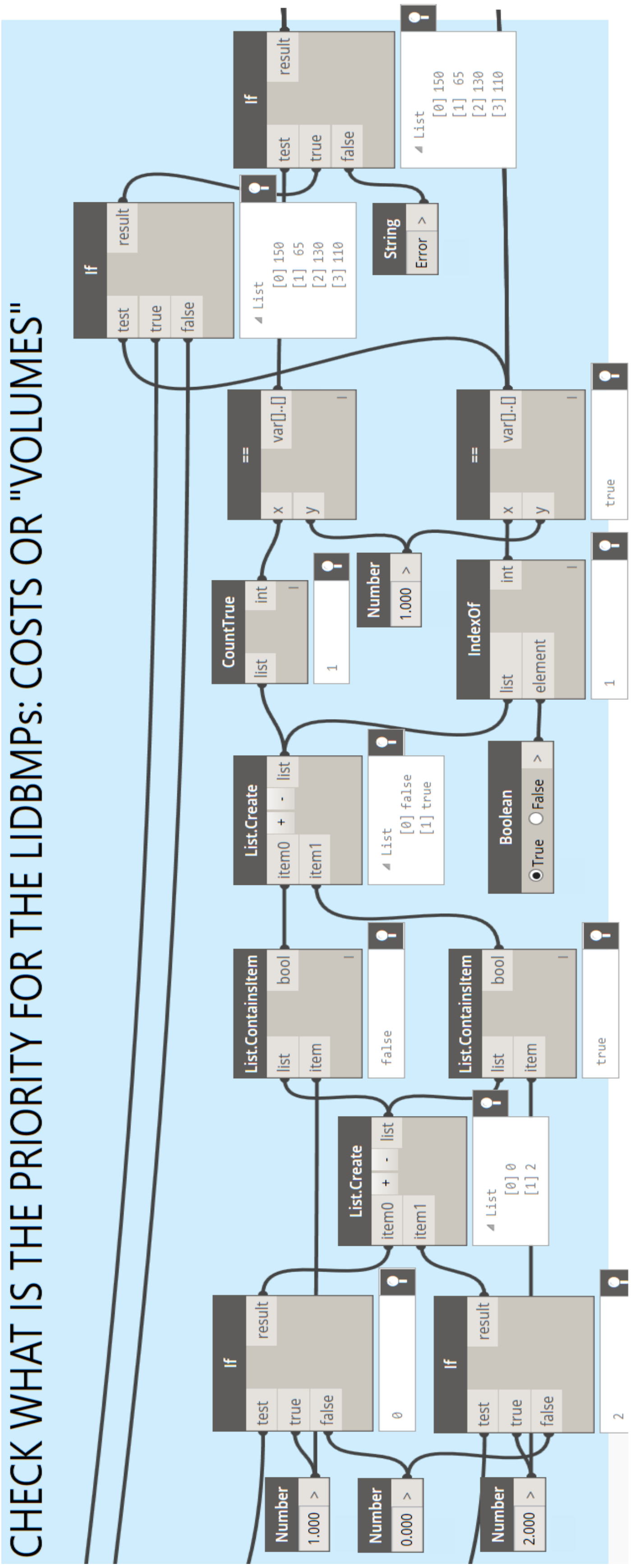

Fig. A.47 – Created Dynamo code to obtain the selected priority information

In Figure A.48, after acquiring the priority information, by using the indexes retrieved in section A.2.5. alongside the "List.GetItemAtIndex" nodes, the retrieved information is matched with the LID-BMP introduced by the user. This not only eliminates the information that does not correspond to any of the chosen LID-BMP (by using the "Manage.RemoveNulls" node), but also reorganizes the list order to correctly correspond to the order introduced by the user. As such, in this example, the [0] index should display the 110 euros per Rain Barrels, which it does.

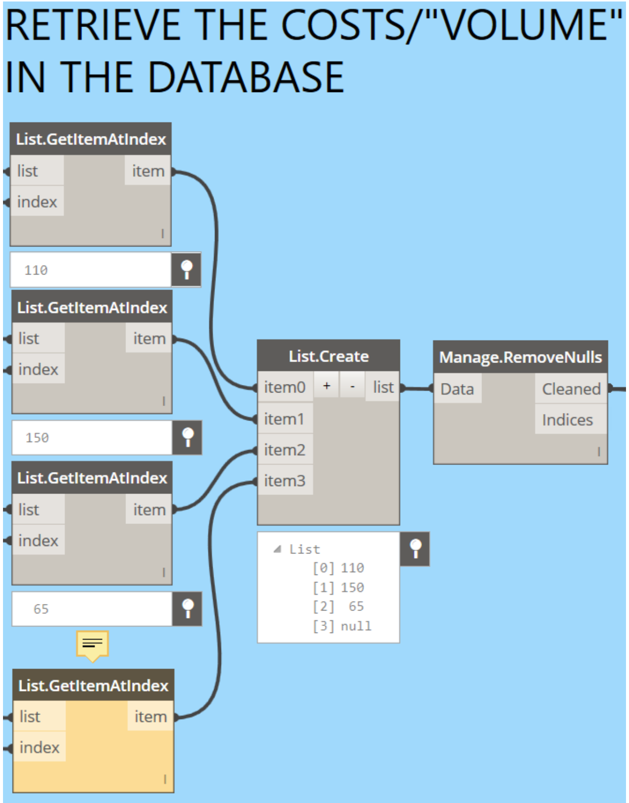

Fig. A.48 – Created Dynamo code to reorganize the retrieved information accordingly to the user selected LID-BMP and respective order

A.2.7. Analyze if the introduced LID-BMP contain Rain Barrels/Cisterns

As a last step before calculating the required LID-BMP areas and costs, since the Rain Barrels/Cisterns storage volume is placed in the same list that the other LID-BMP runoff coefficients, if the minimum area priority is selected alongside the Rain Barrels/Cisterns, the software must identify this occurrence and correctly separate both the runoff coefficients and the storage volume. As such, in Figure A.49 the software starts by checking if the list contains any number superior to "1". However, although the cost list seen in Figure A.48 contains numbers superior to "1", since it has not yet been changed from string to number, the software concludes that there are not any value superior to one, thus eliminating this process. Yet, if the minimum area priority had been selected, the runoff coefficient list (which had already been changed to number in section A.2.4.) would have been retrieved, resulting in the "Equal" node acquiring a "true" value and the "List.GetItemAtIndex" node obtaining the volume of 208 liters from the previously created list.

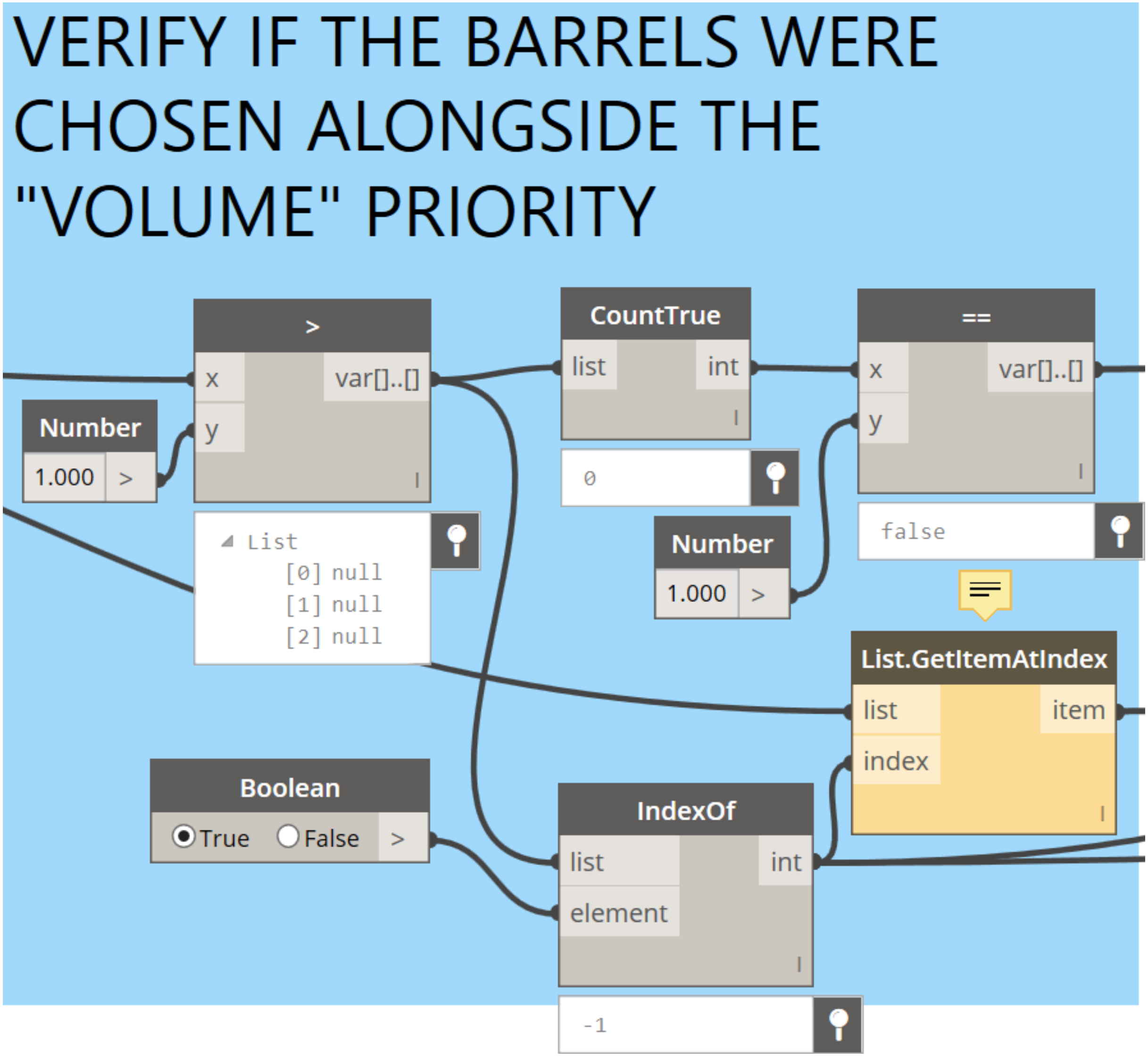

Fig. A.49 – Created Dynamo code to separate the runoff coefficients and storage volumes

A.2.8. Initiate the process of eliminating the runoff

In this step the actual process of mitigating the rainfall runoff is started. It should be stressed that the full process of eliminating it will not be displayed in this attachment since it has quite a few iterations programmed in it. In fact, there are four pieces of code fairly similar to each other but only one them (the second iteration) will be displayed. However, for the reader to grasp the whole process a brief explanation is done in this section.

As such, the software starts by acquiring the priority list created in section A.2.6. Afterwards, since there are four consecutive iterations, the software populates each of them (in the inverse priority order) with the LID-BMP introduced by the user. The software then starts calculating, from the first priority LID-BMP, the mitigated runoff volume which is then subtracted to the volume obtained in Figure A.34. The result is sent to the next LID-BMP iteration. If this value reaches zero the software stops and tells Dyno the required LID-BMP and respective areas and cost. Otherwise, if by the end of the last iteration, the result has yet to reach zero, the software tells Dyno that the chosen LID-BMP are not capable of mitigating enough runoff to achieve the chosen LEED credit or the desired final runoff.

In Figure A.50, A.51 and A.52 it is possible to see the first steps in each of these iterations, which are to eliminate the already used LID-BMP from the priority list, check if there are any left and, if there is, to acquire the correct value from the priority list. As such, starting with Figure A.50, it is possible to perceive an “IndexOf” and a “List.RemoveItemAtIndex” nodes which are used to obtain the index of the LID-BMP studied in the current iteration and eliminating it from the priority list that will be sent to the next iteration. Then, in Figure A.51, the “Object.IsNull” node is used to check if the sent list is empty or, in other words, if all the LID-BMP have been eliminated. If it is true, the process stops and sends the information to Dyno or, if it is false, the iteration process continues. Finally, in Figure A.52, if there are still LID-BMP in the priority list, the lower “If” node, which is connected to the lower “Equal” node in Figure A.47, determines if the minimum or maximum item should be retrieved from the priority list, respectively for the “minimum area” and “minimum cost” priorities. Then, the upper “If” node, which is connected to the “Priority BMP order?” input node seen in section A.2.6, retrieves the last listed item in the priority list if the connected input is true or, if it is false, maintains the value obtained from the previous “If” node. As stated earlier, by analyzing the order in which each priority retrieves values from the “priority list”, it is easily perceived that the population of the iterations is done in the reverse order.

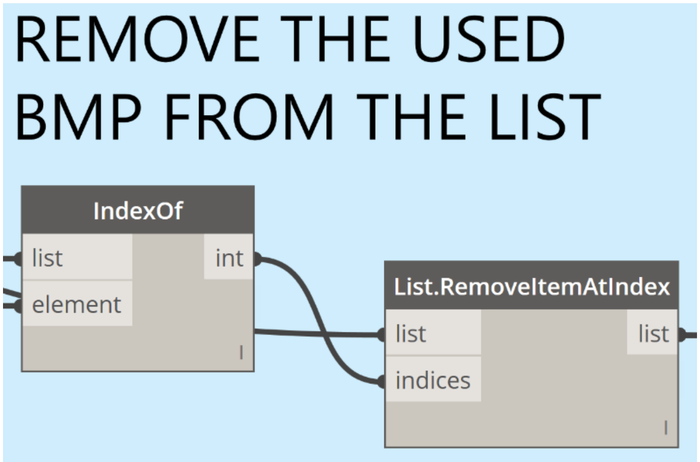

Fig. A.50 – Created Dynamo code to remove used LID-BMP from the priority list

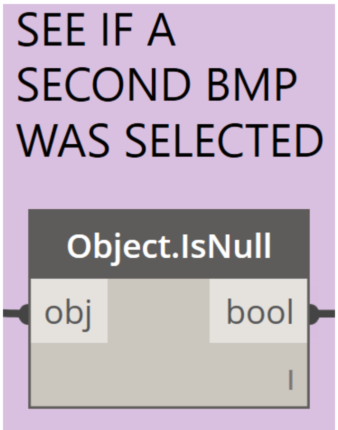

Fig. A.51 – Checking if the priority list is empty

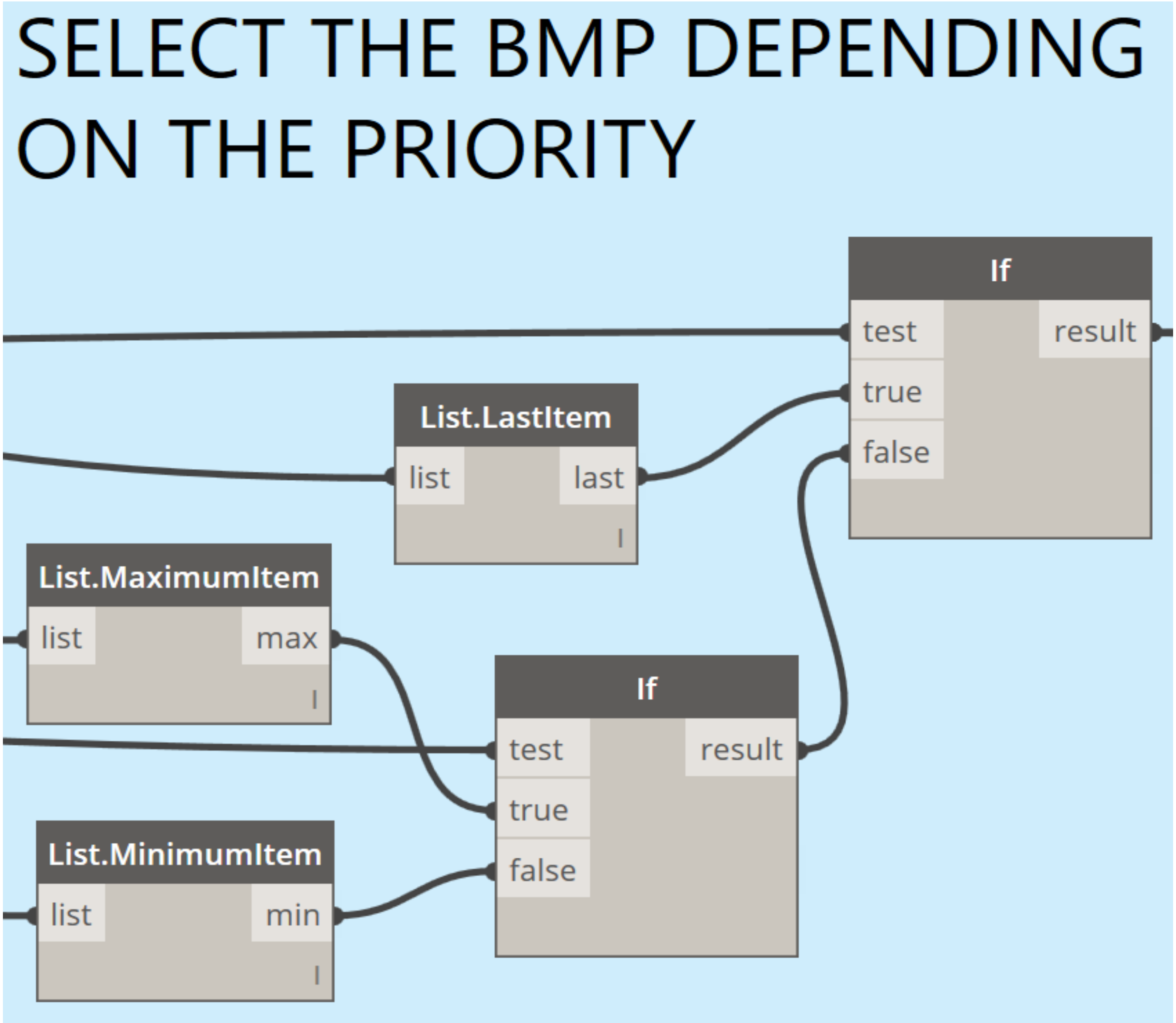

Fig. A.52 – Created Dynamo code for populating the iterations

It should be noted that in this example, and as stated in A.2.6., the “priority order” is selected which means it overrides the “minimum cost” priority, thus creating the following order: Rain Barrels/Cisterns > Green Roof > Permeable Pavement.

A.2.9. OBTAIN ALL THE NECESSARY INFORMATION REGARDING THE INTRODUCED LID-BMP

After selecting the correct LID-BMP for each iteration, the software acquires all the necessary information regarding those same LID-BMP. For instance, in Figure A.53, and keeping in mind this is the second iteration, the information regarding the Green Roofs is obtained. This is done through the application of a few “List.GetItemAtIndex” nodes alongside the “IndexOf” node, which retrieves the selected LID-BMP index. As such, the Green Roof name, cost per square meter, runoff coefficient, and even the available Roof area are easily retrieved and prepared for future use.

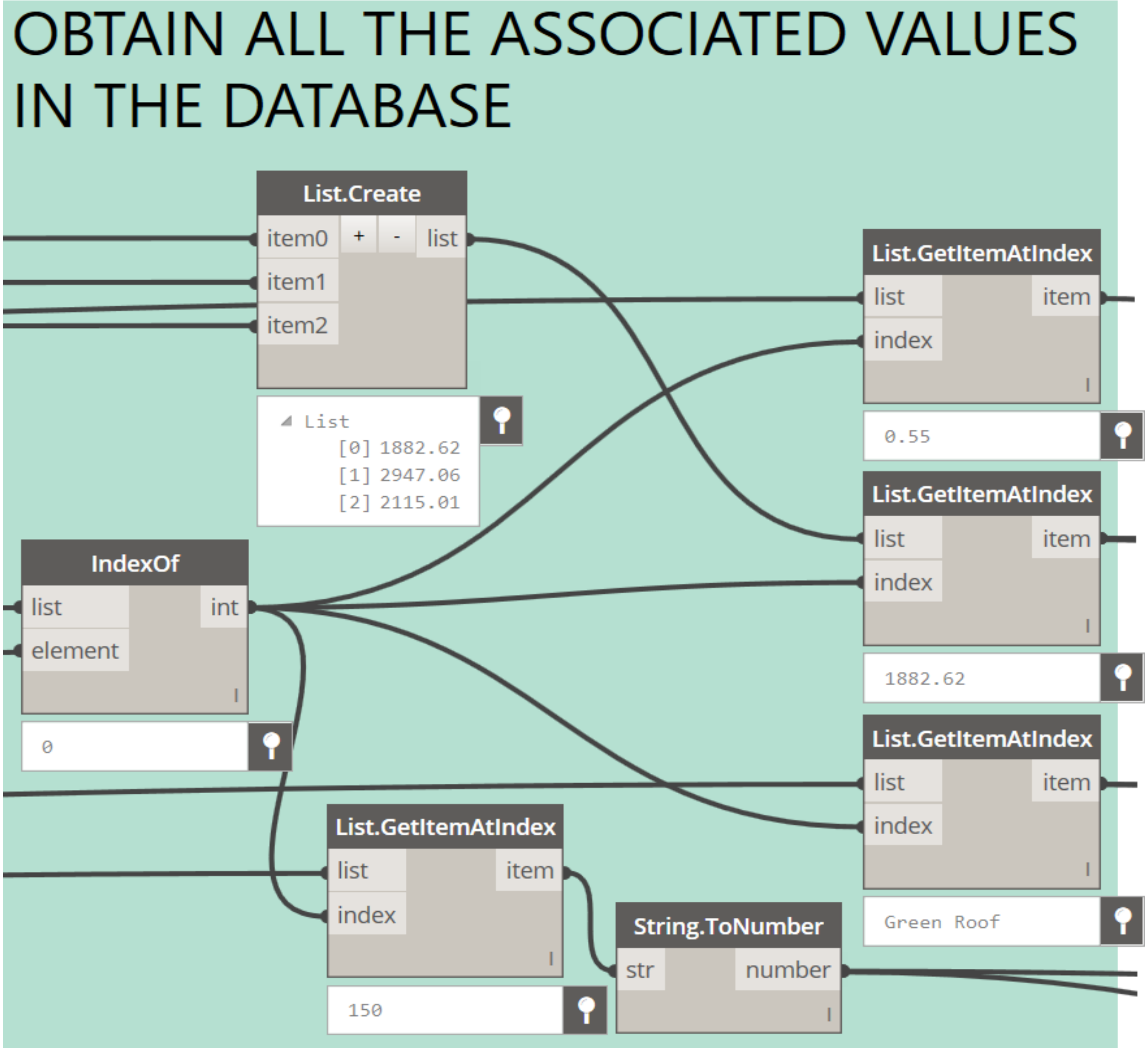

Fig. A.53 – Created Dynamo code to acquire all the necessary information regarding the iteration LID-BMP

A.2.10. Subtract the already mitigated runoff and obtain the necessary area or number for the respective LID-BMP

Acquired the necessary information for the iteration, the next step is to obtain the remaining runoff to be mitigated. Obviously, for the first iteration, this value would equal the full amount of runoff that the user wants to eliminate, but for the remaining ones, as stated in section A.2.8., this value has to be decreased after the iterations are complete. As such, in Figure A.55, a "Subtraction" node is used with the purpose of eliminating the already mitigated runoff.

This acquired result is then used in Figure A.56 and A.57 to obtain the necessary number of barrels or area respectively. Being the second iteration, the software is computing the Green Roof and not the Rain Barrels/Cisterns. However, because of limitations regarding Dynamo, this last LID-BMP as to always be calculated and afterwards removed if the software determines that the iteration's LID-BMP is different from the Rain Barrels/Cisterns. This verification is done using the "Object.IsNull" node seen in Figure A.54 which, when connected to the node containing the Category area in Figure A.53, determines if the selected LID-BMP is the Rain Barrels/Cisterns. This is possible since the barrels do not retrieve any Category area from the created list, since they are conditioned by the maximum number of barrels and not the available area. As such, if in fact the Rain Barrels/Cisterns are selected, the node containing the Category area will be empty, attributing a true value to the "Object.IsNull" node.

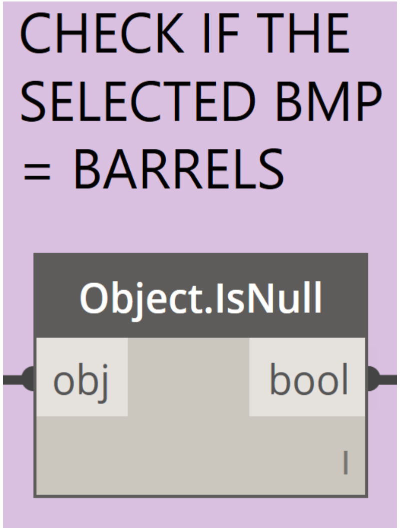

Fig. A.54 – Check if the iteration LID-BMP equals the Rain Barrels/Cisterns

This way, starting with the Dynamo code for the Rain Barrels, in Figure A.56 the necessary number of barrels is calculated through the division of the remaining runoff to be eliminated and the storage volume of 208 liters for each barrel. The result is then rounded up to acquire a unitary number of barrels which, in this case, is 50. Subsequently, the value is compared with the maximum number of barrels introduced by the user, which was 10, and an "If" node is used in Figure A.57 to acquire the correct number of barrels (10 if the comparison is false, or the obtained value if it is true – in this example, since the obtained value was 50, the software acquires the value of 10 barrels).

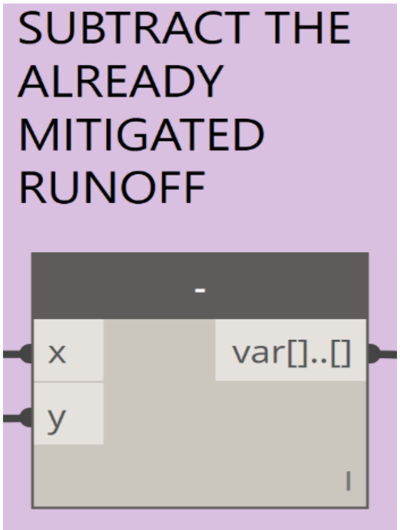

Fig. A.55 – Node used to obtain the remaining runoff volume to be eliminated

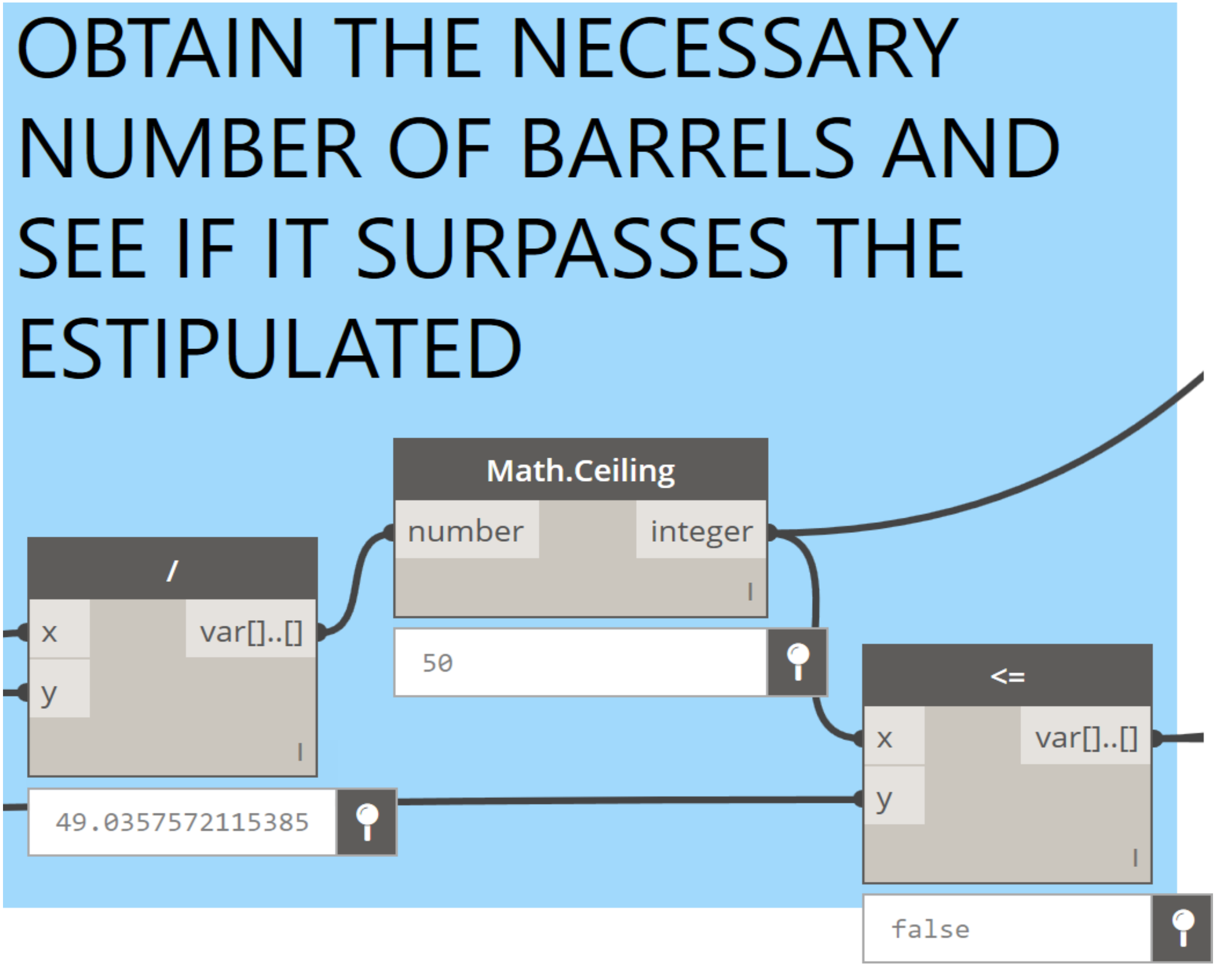

Fig. A.56 – Created Dynamo code to acquire the necessary number of Rain Barrels/Cisterns

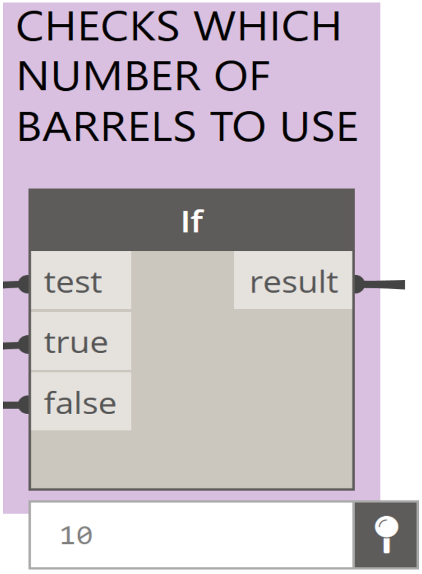

Fig. A.57 – Check if the obtain number of Rain Barrels/Cisterns exceeds the maximum number imposed by the user and choose the used value accordingly

In Figure A.58, regarding the Green Roof or any other LID-BMP using runoff coefficients, the process is similar, but this time the software has to apply equation 1.0 to obtain the necessary area to be used. As such, the storm intensity and duration obtained from the first half of the software have to introduce in Dyno. The intensity is then multiplied by the runoff coefficient acquired in Figure A.53 and by a thousand to obtain the value in L/h. At the same time the duration is converted to hours using the same process as in Figure A.31. Both this values are then multiplied by each other to acquire the volume dependent on the area, in this case:

$$Runoff\ Volume = 7.517 \times Area$$

As such, in agreement with the above equation, by dividing the volume to be eliminated by the multiplication result (7.517 L/m^2), the software obtains the required area. In a process similar to the one regarding the maximum number of barrels, the area required for the Green Roof is then compared with the Roof area obtained in Figure A.53. Depending on the result the "If" node is Figure A.59 sends forward the calculated value or the maximum Roof area. In this case, since by using 10 Rain Barrels (result from the first iteration which is not displayed in this Attachment) plus 1356 square meters of Green Roof (result of this second iteration) the LEED O+M credit (credit chosen by the user in Figure A.32 and A.33) is acquired, the value displayed by the "If" node is the one calculated in Figure A.58.

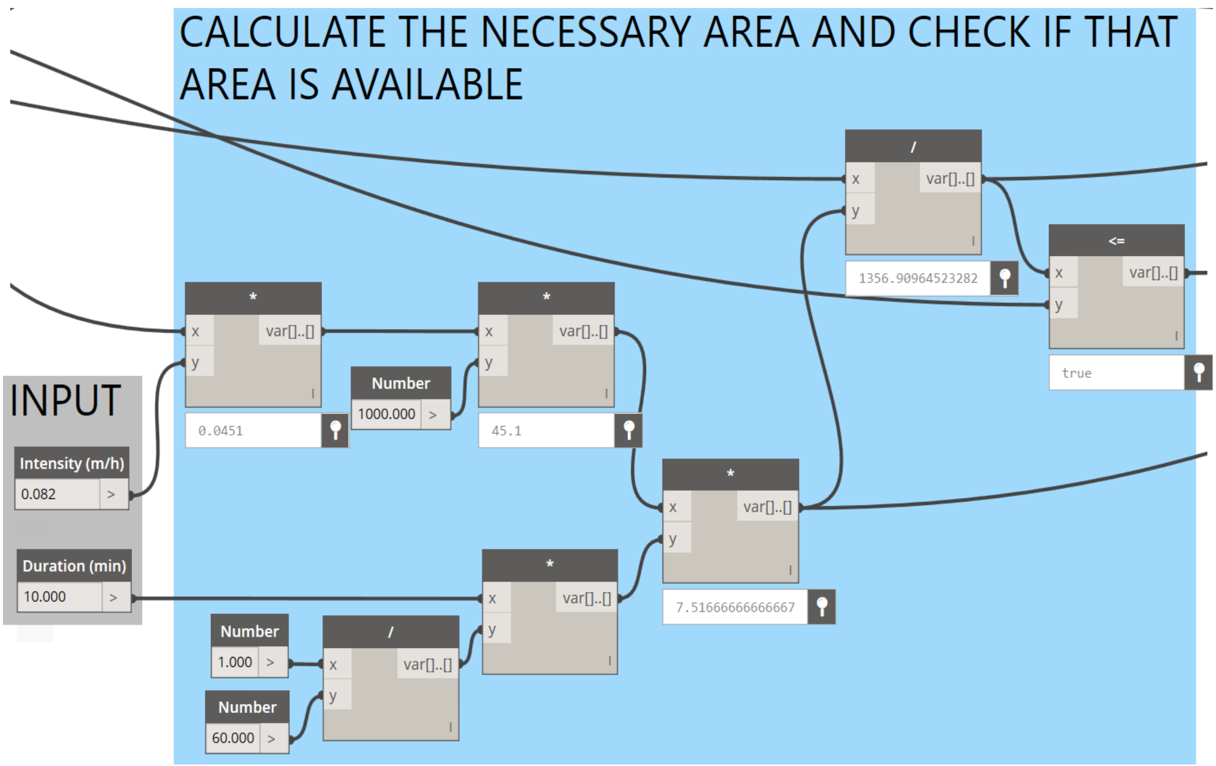

Fig. A.58 – Created Dynamo code to acquire the necessary area of Green Roof

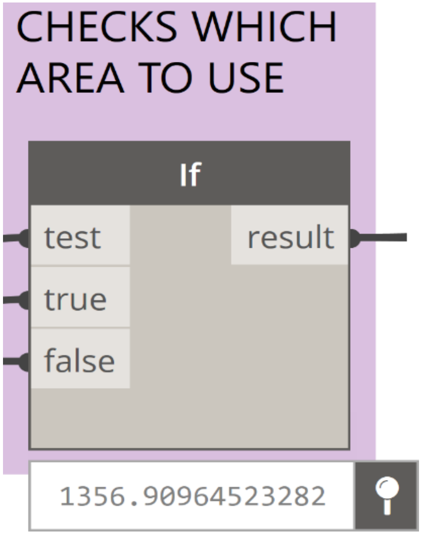

Fig. A.59 – Check if the obtain area of Green Roof exceeds the maximum Roof area obtained from the first half of the software

A.2.11. Calculate the mitigated volume with the current LID-BMP

Acquired the total number of required barrels and area, the values are multiplied in Figure A.60 by the corresponding volumes, in the Rain Barrels/Cisterns case 208 liters, and in the Green Roof case the obtained value of 7.517 L/m^2. These values are then summed with the volume from the previous iterations in Figure A.61, to be mitigated in the beginning of the next iteration.

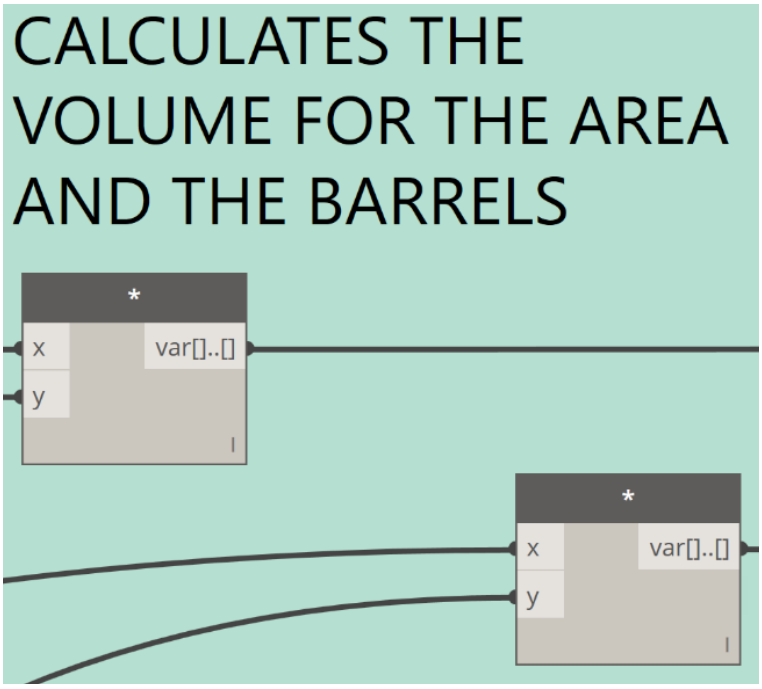

Fig. A.60 – Obtain the mitigated volume in the iteration using the selected LID-BMP

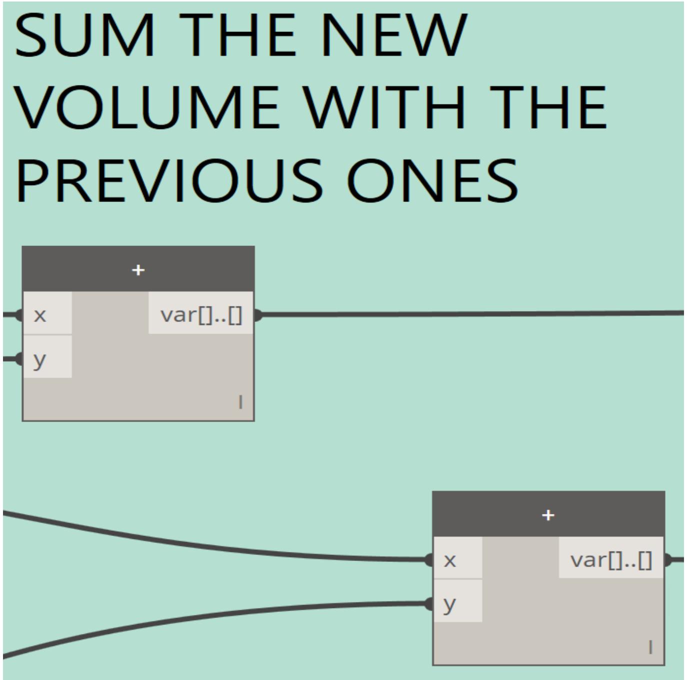

Fig. A.61 – Sum the already mitigated runoff from previous iterations with the one obtained in the previous figure

A.2.12. Create a string to relay the information to the user

Obtained the area/number of barrels and the respective volume mitigated, the software creates a string containing the applied LID-BMP and the respective cost and area/number of barrels. As such, to obtain the LID-BMP cost, the acquired area/number of barrels are multiplied by the cost retrieved in Figure A.53. This process can be seen in Figure A.62. Afterwards, and still before creating the string, the software has to check if any text has already been created in previous iterations. This verification has to be done since the software may not have populated the previous iteration with any LID-BMP since the user might have decided to not use all four LID-BMP. As such, in Figure A.63 and A.64 a "String.Contains" node is used to check if the previous iteration produced any text and an "If" node is applied to select between the text produced in Figure A.65 or A.66, respectively to create a new string or continue the previous one. The string is created using a "String.Concat" node which simply joins strings together. The LID-BMP name as well as the respective area/number of barrels and cost are introduced in the string using "Code Blocks" and "String from Array" nodes. In the case a new string is created the following string is obtained: "Desired runoff obtained using #area square meters of #name with a total cost of #cost €.". However, if the software continues a previous string, the final point in the prior sentence is replaced with a comma and the following string is attached to the previous one created: "…, plus #area square meters of #name with a total cost of #cost €". It should be noted that two separate strings are created for the Rain Barrels LID-BMP using slightly the same code.

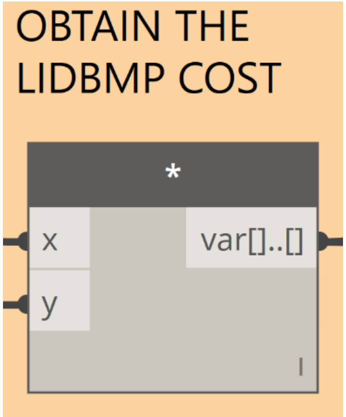

Fig. A.62 – Obtain the total cost regarding the iteration LID-BMP

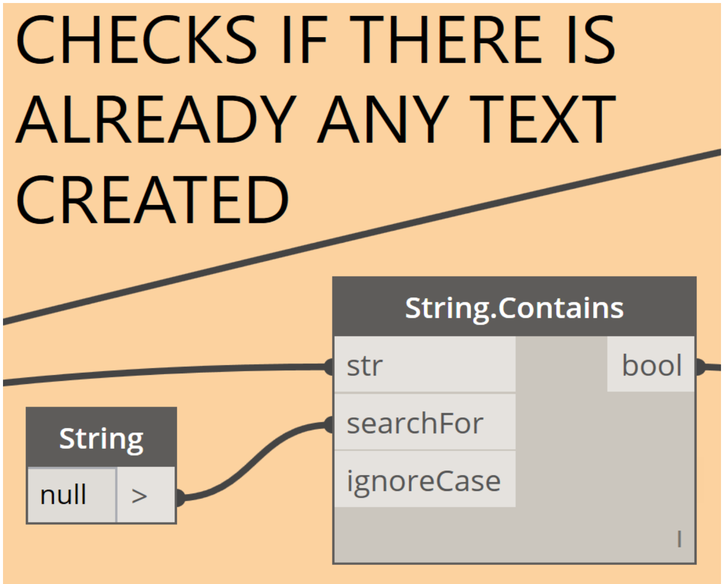

Fig. A.63 – Checks if any text has already been created in previous iterations

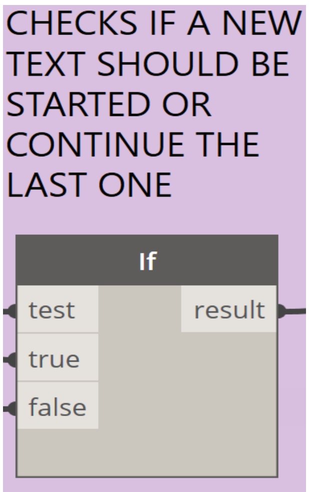

Fig. A.64 – Selects between the creation of a new string and the continuation of a previous one

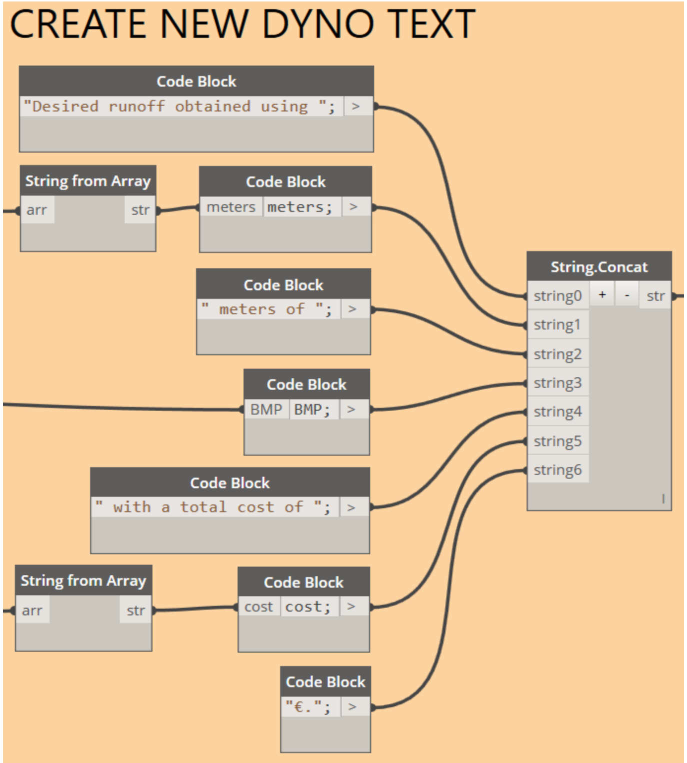

Fig. A.65 – Created Dynamo code to generate a new string

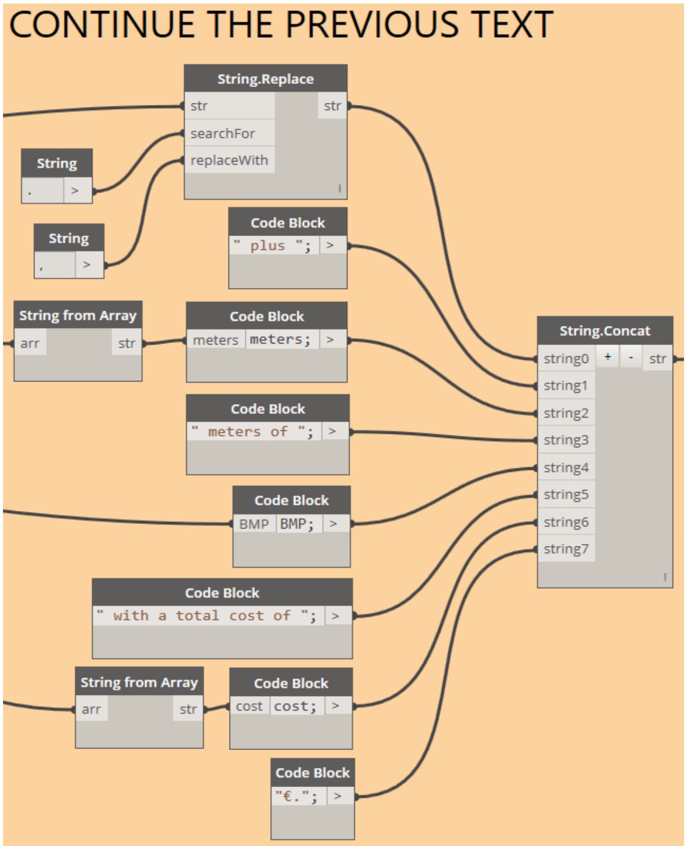

Fig. A.66 – Created Dynamo code to continue a previous generated string

A.2.13. Final checks before sending the information to Dyno

Before starting the final steps of sending the information to Dyno a few more "If" nodes have to be used for the software to function properly. In fact, five more of these nodes have to be applied: the first, shown in Figure A.67, is used to select which text should be used. This selection is not between the "new string" and the "continuation of the previous string" (that decision is done in Figure A.64), but rather between the strings belonging to the LID-BMP containing runoff coefficients or the ones belonging to the Rain Barrels/Cisterns which, as it was mentioned in the last section, have to be created for the possibility of the Rain Barrels/Cisterns being the selected LID-BMP. To do so, the "If" node is linked with the "Object.IsNull" node seen in Figure A.54. The obtained result is sent to Figure A.68 and also to the next iteration to be checked for a string, just like in Figure A.64.

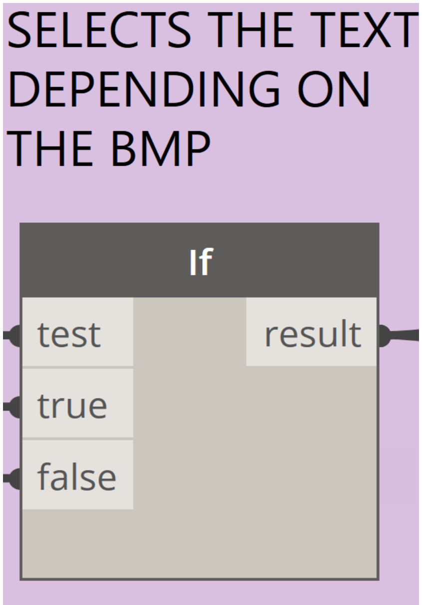

Fig. A.67 – Check which LID-BMP text is sent forward

The next "If" nodes seen in Figure A.68, are used to determine if the runoff to be mitigated has been fully eliminated or not. To do so, the "If" nodes are linked to the comparison nodes seen in Figure A.57 and Figure A.59. If these comparison nodes acquire a "true" value, it means the LID-BMP used in the iteration was not required to be used at its full extent, which means the desired mitigated runoff has been completely eliminated. As such, depending on the comparison value, the "If" nodes can send to the next "If" node in Figure A.69 two types of information: the already mitigated runoff which will be subtracted to the total runoff to be reduced (just like in Figure A.55); or the selected string containing the information to be sent to Dyno.

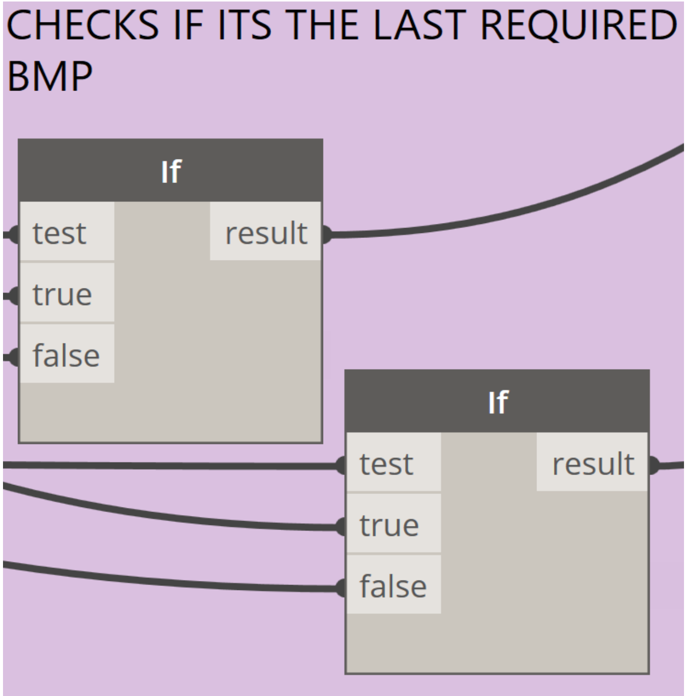

Fig. A.68 – Check which information should be sent forward: the mitigated runoff or the information string

The succeeding "If" node basically has the same purpose as the one seen in Figure A.67. However, in this case, instead of choosing which LID-BMP string should be acquired, the "If" nodes determines which information should be selected from the two "If" nodes seen in Figure A.68. To do so, the "If" node is, once again, linked with the "Object.IsNull" node seen in Figure A.54.

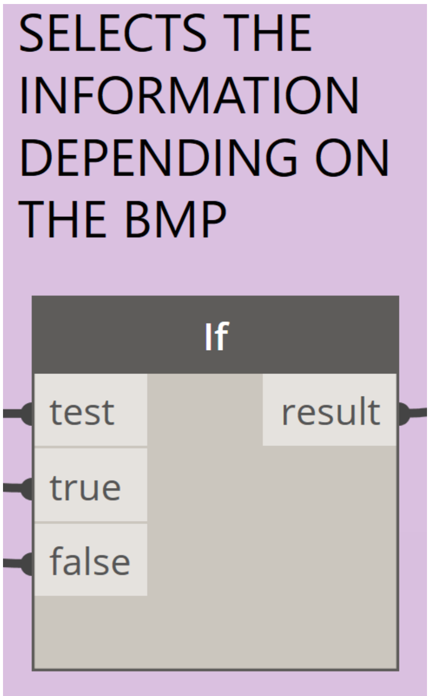

Fig. A.69 – Check which LID-BMP information should be sent forward

Finally, the last “If” node, seen in Figure A.70, is used to prevent the software from crashing. In fact, in the possible case of the user not choosing all four LID-BMP to be used in the mitigation of the initial runoff volume, one or more iterations will remain empty. As such, no information would reach the next iteration causing, for example, the “Subtraction” node seen in Figure A.55 to crash. To resolve this, in case the iteration is empty the value “0” is sent to the next iteration. If not, the information obtained in Figure A.69 is sent instead. To accomplish this comparison, the “Object.IsNull” node seen in Figure A.51 is connected to this last “If” node.

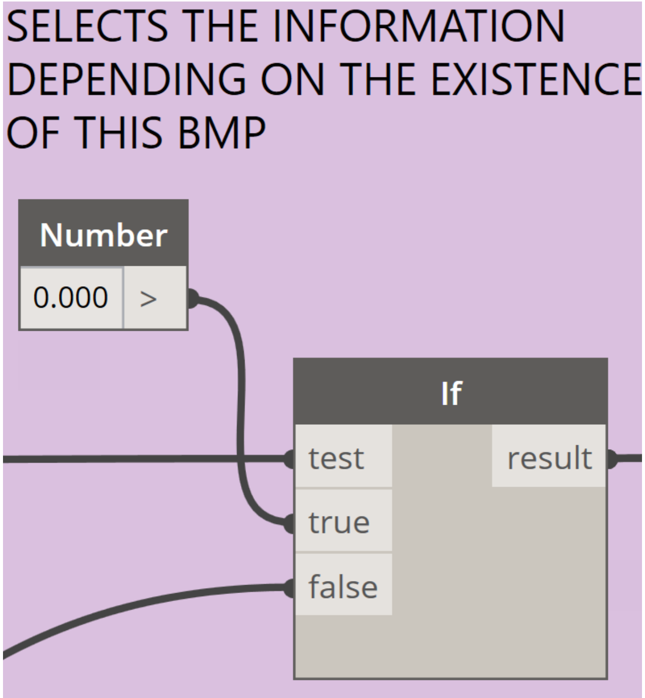

Fig. A.70 – Check if the iteration is empty, sending to the next iteration the value “0” if it is

A.2.14. Manage all the retrieved information from the four iterations

At last, when all the iterations have been correctly run, the software sends each iteration information to Figure A.71. There, by applying a set of “String.StartsWith” nodes alongside the string “Desired”, the software searches for the iteration that sent the used LID-BMP information. If a string containing that information is acquired, it is sent to a newly created list, in the end of Figure A.71, alongside a few “Error” sentences and/or the sentence “It is impossible to obtain the desired runoff.”. For a better comprehension of when each sentence is retrieved, by analyzing Figure A.71, it is possible to understand that the “Error” is obtained when the “String.StartsWith” node does not retrieve any information. This happens when the iteration was not populated (fewer than four LID-BMP) or the iteration results is a mitigation volume and not a string. Next, the “It is impossible to obtain the desired runoff.” string is acquired when the first iteration was not used (because the runoff volume was already mitigated in previous iterations) or the volume fails to be completely mitigated. However, as it will be possible to conclude from Figure A.72, the fact that this string is placed on the created list does not mean the software has failed to achieve the desired final runoff volume. In fact, by analyzing Figure A.72, it is possible to understand that the new list is first searched by the euro sign. If it finds any row containing it, by using a “IndexOf” node alongside a “Boolean” and a “List.GetItemAtIndex” nodes, the LID-BMP information is sent to Figure A.73, if not, the “It is impossible to obtain the desired runoff.” sentence is sent instead.

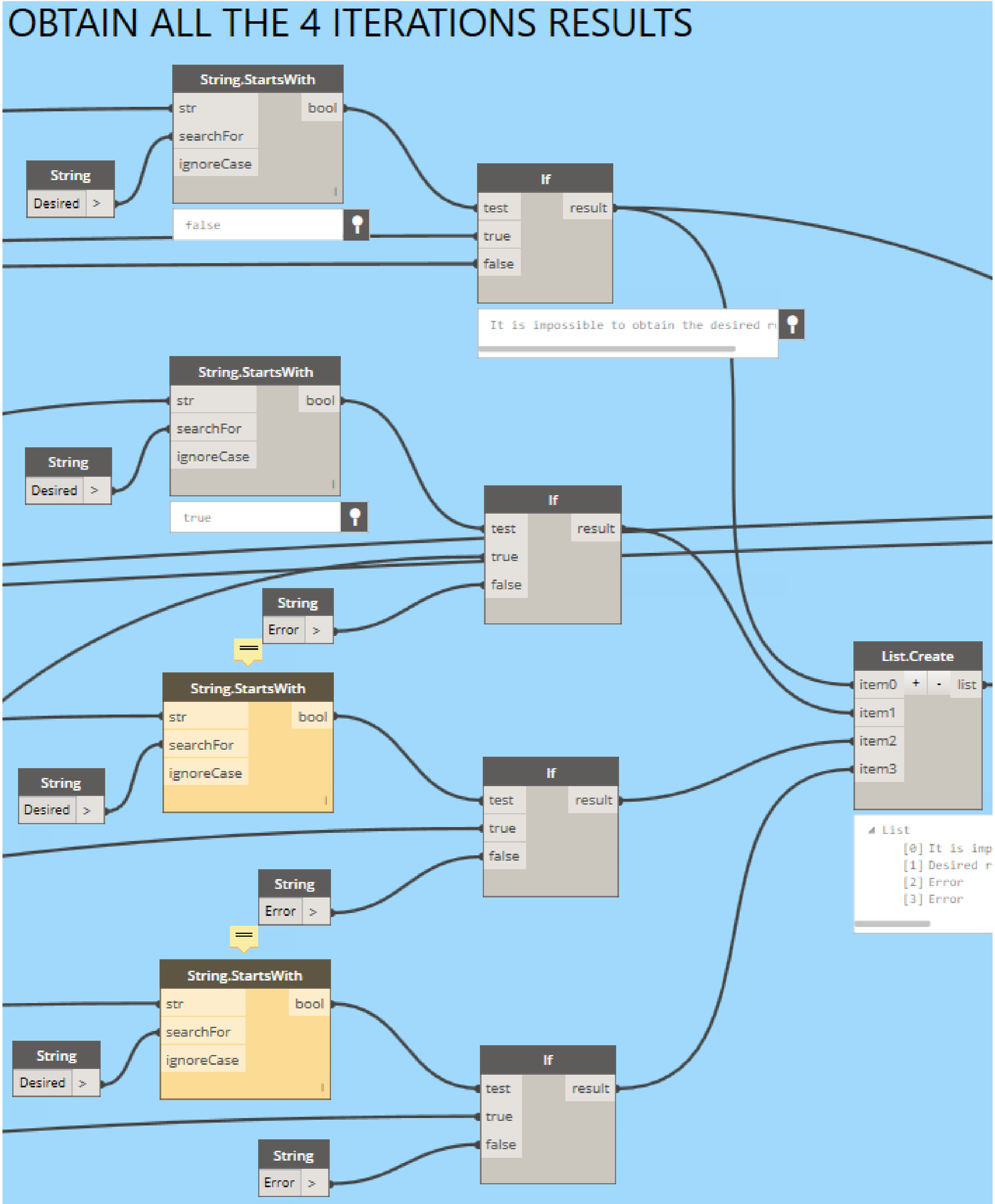

Fig. A.71 – Created Dynamo code to retrieve all the iterations information and group into a single list

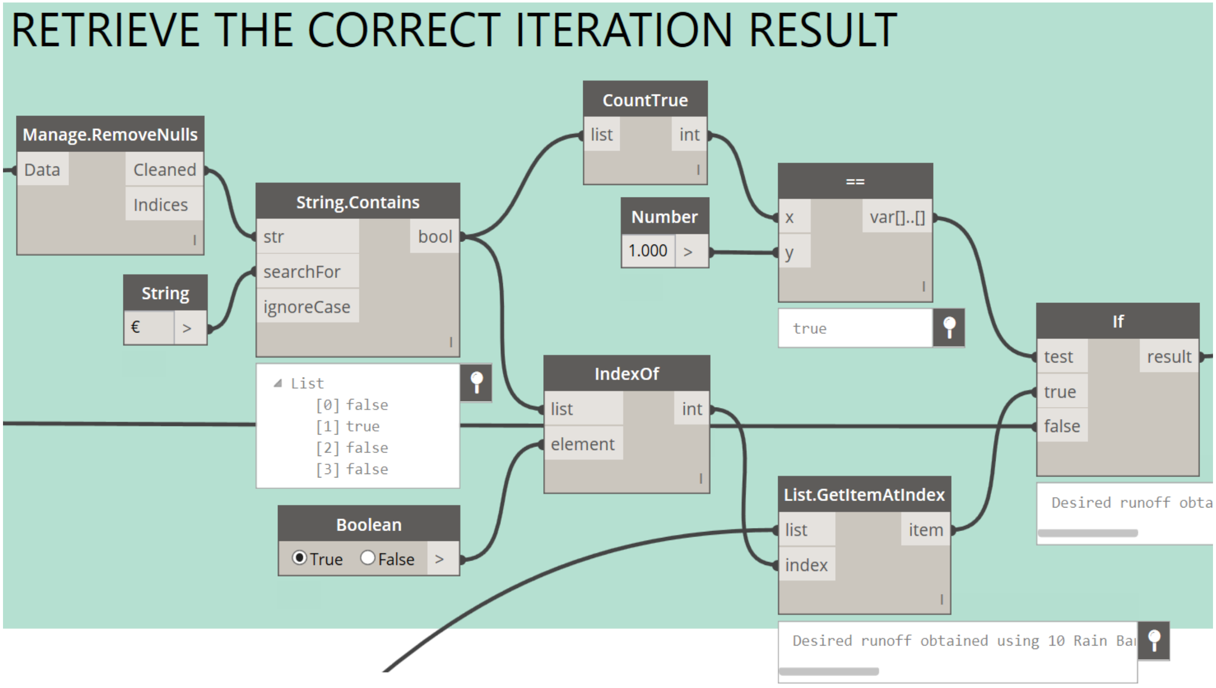

Fig. A.72 – Created Dynamo code to obtain the LID-BMP information inside the iterations or, if there is not any, send the user a failing message

A.2.15. SEND THE OBTAINED INFORMATION TO THE USER

In this final step, as stated in A.2.2, the software checks if the possible chosen credit is the "LEED BD+C: Homes/Multifamily Midrise". This procedure is done using the "If" node in Figure A.73 which retrieves the information from the "Equal" node seen in Figure A.36 and chooses the information to send the user accordingly. If the "Equal" node is true, then the information regarding this LEED credit is displayed to the user, if not, the necessary LID-BMP to correct the runoff, along with the respective areas and costs, are displayed. The actual sending of information is done through the "Watch" node in Figure A.74.

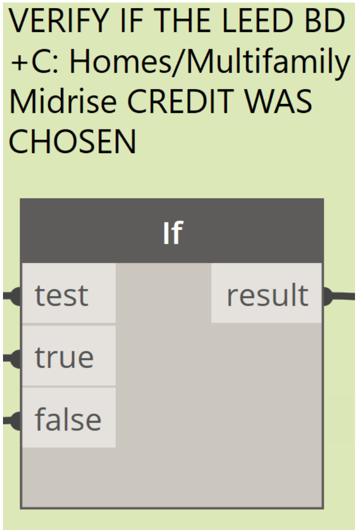

Fig. A.73 – Verify if the possible chosen credit equals the LEED BD+C: Homes/Multifamily Midrise

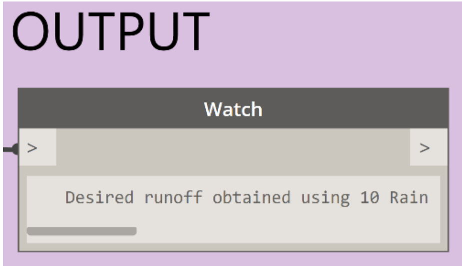

Fig. A.74 – Send the computed information to Dyno

Lacing is a Dynamo functionality for processing lists and data management. This ability typically offers three lacing option: “Shortest”, “Longest” and “Cross Product”. By default, nodes work with the “Shortest” lacing option, however it can be switched by accessing each node properties. Understanding how lacing works is a crucial point of Dynamo since it helps to understand how Dynamo computes solutions and manages data inside lists. In order to help the reader better understand the designed software code, the following sections contain two examples of this functionality and will be thoroughly explained through the creation of number sequence lists.

A.3.1. First example

For the first example the “Number Range” node is used. As the name suggests, this node creates a sequence of numbers inside a pre-determined range. As seen in Figure A.75, the created list contains a number sequence starting on “0” and ending on “10” using a step of “2”. By linking this list to the “Point.ByCoordinates” node “X” and “Y” inputs, a series of six points containing these coordinates is created and can be seen in Figure A.76.

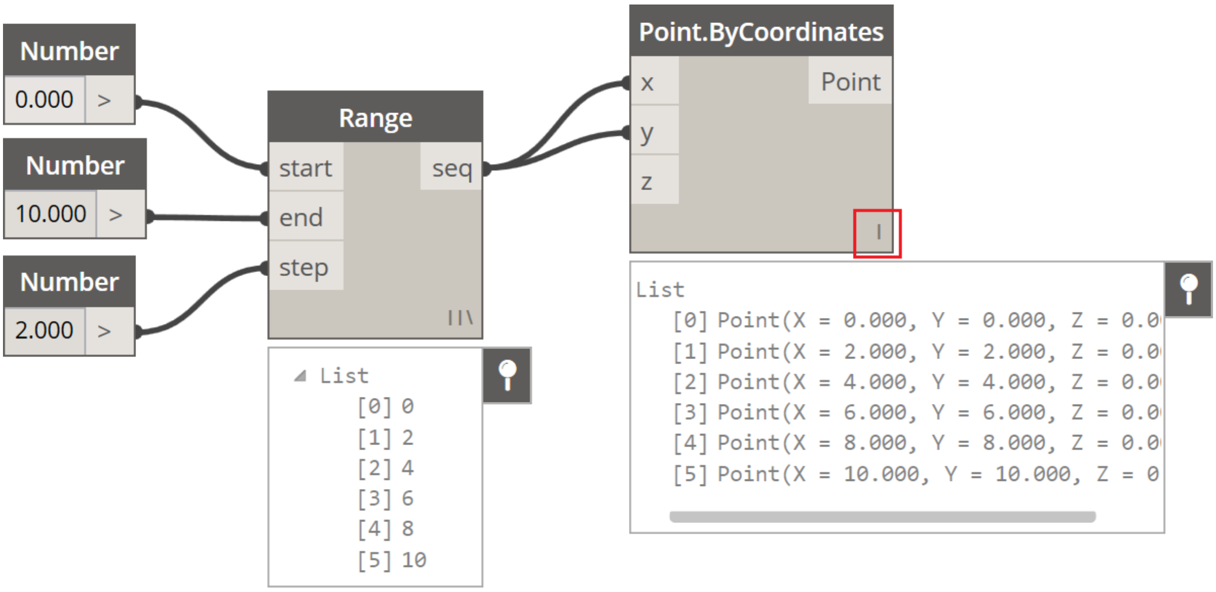

Fig. A.75 – “Point.ByCoordinates” node set to “Shortest” lacing

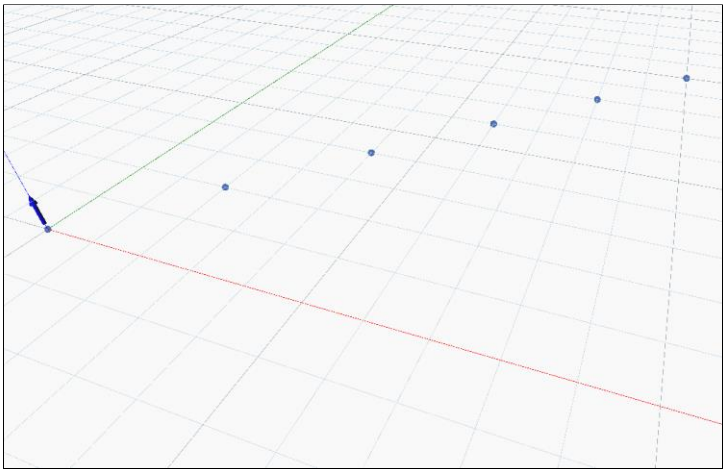

Fig. A.76 – “Point.ByCoordinates” node set to “Shortest” lacing – 3D representation

However, this happens since the “Point.ByCoordinates” node is set to the lacing option “Shortest” (seen in Figure A.75 through the “|” mark on the bottom right corner of the node), which translates in the acquirement of the shortest representation between the two “X” and “Y” inputs. By changing the lacing option to “Cross Product” (seen in Figure A.77 through the “xxx” mark on the bottom right side of the node), the node retrieves the full representation of the inputs, originating the series of points seen in Figure A.78.

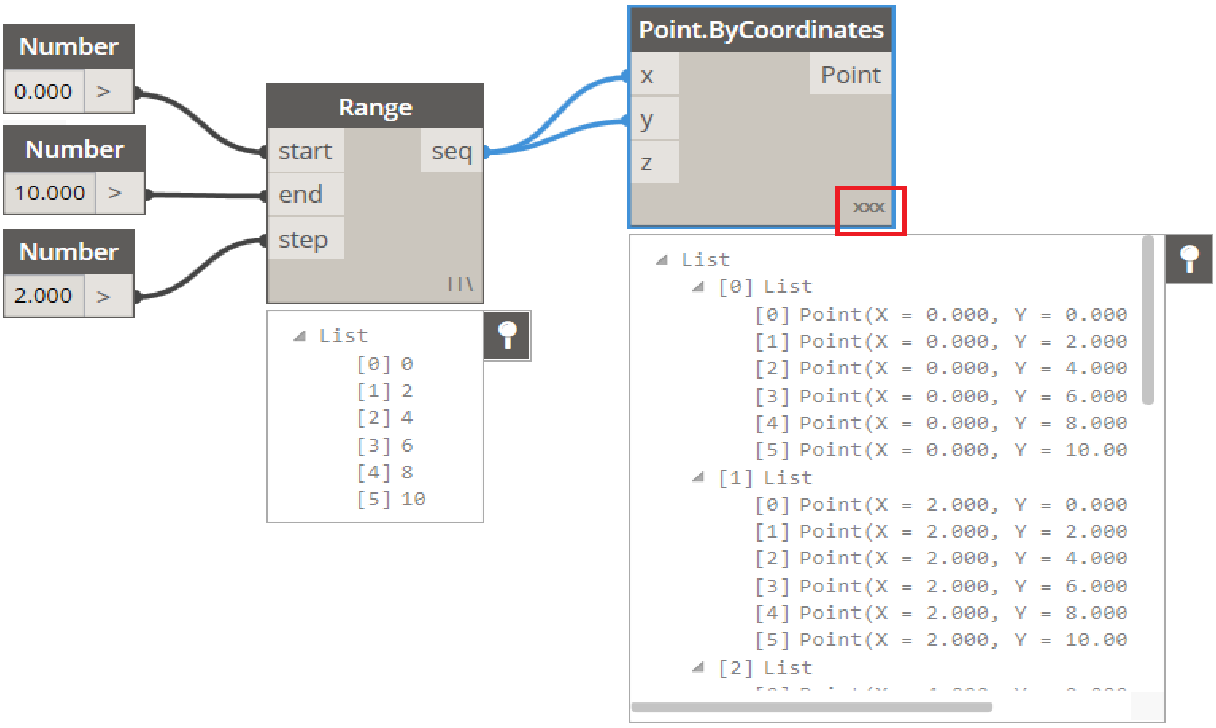

Fig. A.77 – “Point.ByCoordinates” node set to “Cross Product” lacing

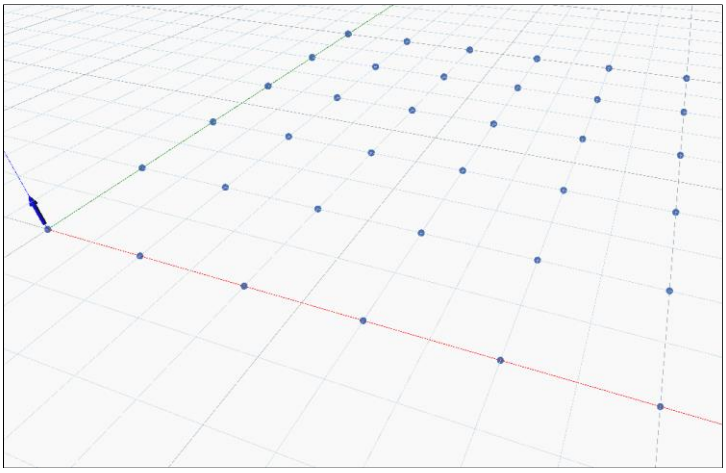

Fig. A.78 – “Point.ByCoordinates” node set to “Cross Product” lacing – 3D representation

A.3.2. Second example

For this next example, the previous nodes will be used alongside the “Sequence” and “Line.ByStartPointEndPoint” nodes. As the name suggests, the “Sequence” node creates a sequence containing a determined amount of numbers. In Figure A.79, the resulting list retrieved from this node contains a sequence of “15” numbers starting in “0” with a step of “1”.

Just like the previous example, both lists are used to create points through the “Point.ByCoordinates” node, though this time all the points are situated in the X plane as seen in Figure A.80.

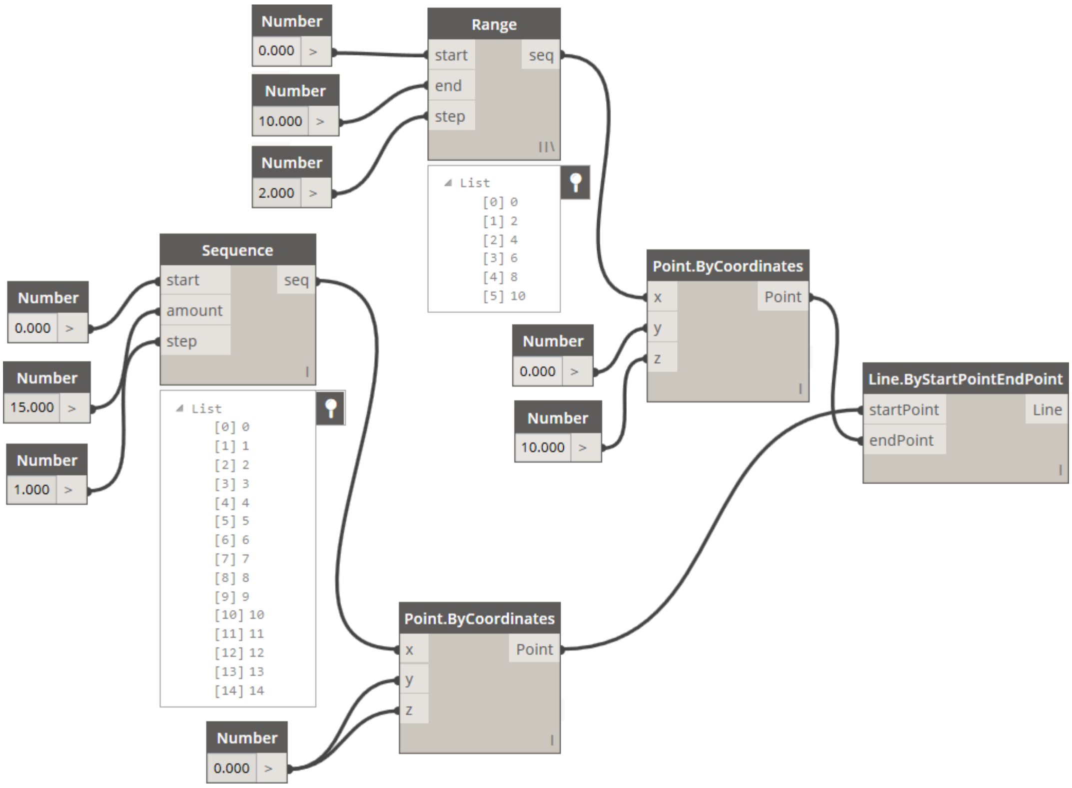

Fig. A.79 – Creating sequences, points and lines inside Dynamo

By linking both “Point.ByCoordinates” nodes to the “Line.ByStartPointEndPoint” node, lines connecting both set of points are created in the X plane. These lines offer different results depending on the lacing option. By using the “Shortest” option, Dynamo only computes the smaller list solutions, leaving the remaining bottom side points without a line. However, using the “Longest” option, Dynamo uses the last point in the shortest list to create the remaining set of lines connecting both lists, offering solutions for all the points inside the longest list. Finally, by using “Cross Product”, all possible solutions are computed by Dynamo. All the solutions can be seen in Figures A.81, A.82 and A.83.

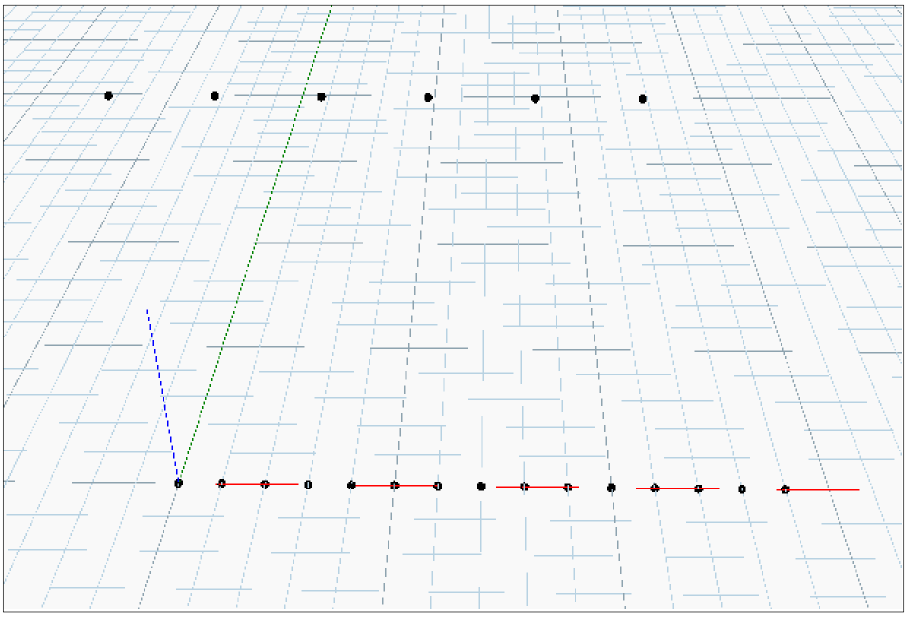

Fig. A.80 – Created points

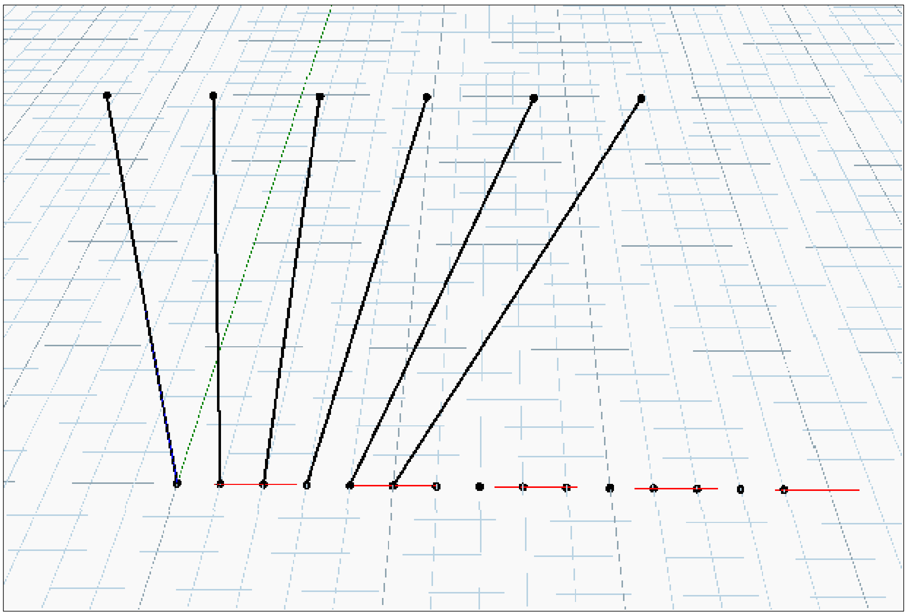

Fig. A.81 – “Shortest” lacing

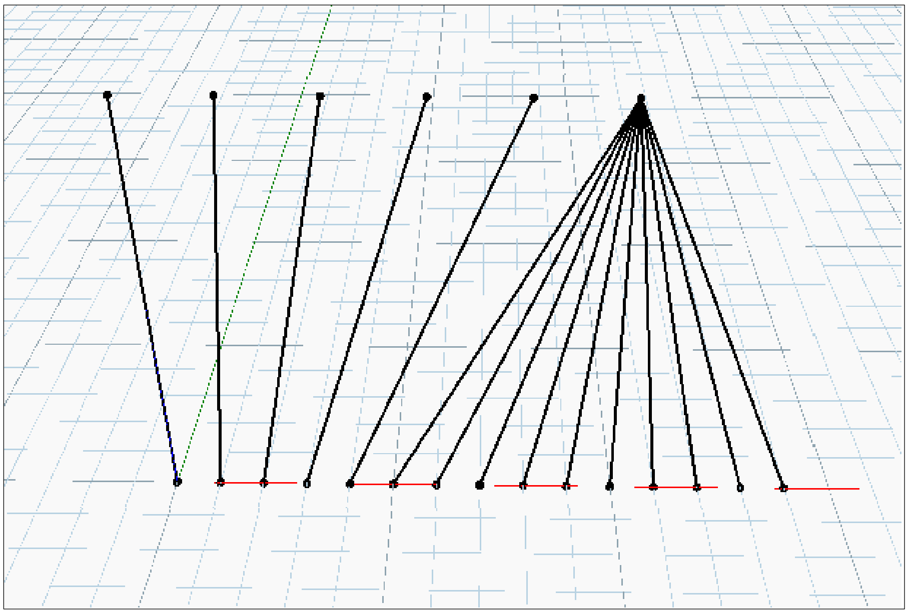

Fig. A.82 – “Longest” lacing

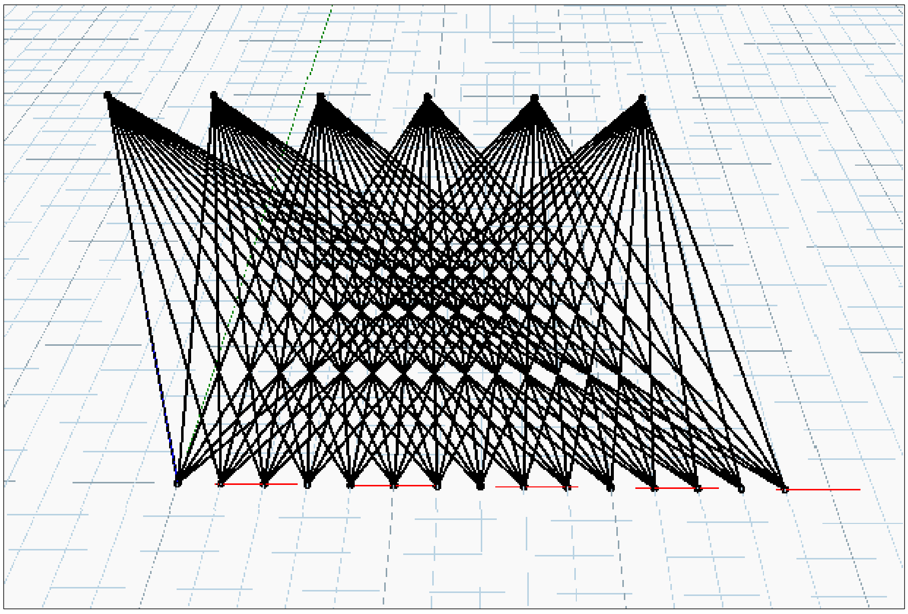

Fig. A.83 – “Cross Product” lacing

ATTACHMENT B

XML AND DPR FILES

B.1. RUNOFF COEFFICIENTS.XML


```xml
<?xml version="1.0" encoding="UTF-8" ?>
<Table>
    <Element>
        <Element>
            <Name>Residential</Name>
            <RunoffCoefficient>0.50</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Business</Name>
            <RunoffCoefficient>0.75</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Industrial</Name>
            <RunoffCoefficient>0.70</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Lawns</Name>
            <RunoffCoefficient>0.20</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Playgrounds</Name>
            <RunoffCoefficient>0.30</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Parks/Cemeteries</Name>
            <RunoffCoefficient>0.20</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Walks</Name>
            <RunoffCoefficient>0.80</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Streets</Name>
            <RunoffCoefficient>0.85</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Forest</Name>
            <RunoffCoefficient>0.15</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Meadow</Name>
            <RunoffCoefficient>0.30</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Agricultural land</Name>
            <RunoffCoefficient>0.35</RunoffCoefficient>
        </Element>
        <Element>
            <Name>Roof</Name>
            <RunoffCoefficient>0.85</RunoffCoefficient>
        </Element>
    </Element>
</Table>
```

B.2. BMP.XML


```xml
<?xml version="1.0" encoding="UTF-8" ?>
<Table>
        <LIDBMP>
            <Name>Green Roof</Name>
            <RunoffCoefficient>0.30</RunoffCoefficient>
            <Cost>150</Cost>
        </LIDBMP>
        <LIDBMP>
            <Name>Permeable Pavement</Name>
            <RunoffCoefficient>0.25</RunoffCoefficient>
            <Cost> 65</Cost>
        </LIDBMP>
        <LIDBMP>
            <Name>Rain Gardens/Swales</Name>
            <RunoffCoefficient>0.1</RunoffCoefficient>
            <Cost>130</Cost>
        </LIDBMP>
        <LIDBMP>
            <Name>Rain Barrels/Cisterns</Name>
            <RunoffCoefficient>208</RunoffCoefficient>
            <Cost>110</Cost>
        </LIDBMP>
</Table>
```


B.3. INTENSITY COEFFICIENTS.XML


```xml
<?xml version="1.0" encoding="UTF-8" ?>
<Table>
    <PeriodData>
            <Period>2</Period>
            <Aa>202.72</Aa>
            <Ab>-0.577</Ab>
            <Ba>162.18</Ba>
            <Bb>-0.577</Bb>
            <Ca>243.26</Ca>
            <Cb>-0.577</Cb>
    </PeriodData>
    <PeriodData>
            <Period>5</Period>
            <Aa>259.26</Aa>
            <Ab>-0.562</Ab>
            <Ba>207.41</Ba>
            <Bb>-0.562</Bb>
            <Ca>311.11</Ca>
            <Cb>-0.562</Cb>
    </PeriodData>
    <PeriodData>
            <Period>10</Period>
            <Aa>290.68</Aa>
            <Ab>-0.549</Ab>
            <Ba>232.21</Ba>
            <Bb>-0.549</Bb>
```

```
            <Ca>348.82</Ca>
            <Cb>-0.549</Cb>
    </PeriodData>
    <PeriodData>
            <Period>20</Period>
            <Aa>317.74</Aa>
            <Ab>-0.538</Ab>
            <Ba>254.19</Ba>
            <Bb>-0.538</Bb>
            <Ca>382.29</Ca>
            <Cb>-0.538</Cb>
    </PeriodData>
    <PeriodData>
            <Period>50</Period>
            <Aa>349.54</Aa>
            <Ab>-0.524</Ab>
            <Ba>279.63</Ba>
            <Bb>-0.524</Bb>
            <Ca>419.45</Ca>
            <Cb>-0.524</Cb>
    </PeriodData>
    <PeriodData>
            <Period>100</Period>
            <Aa>365.62</Aa>
            <Ab>-0.508</Ab>
            <Ba>292.50</Ba>
            <Bb>-0.508</Bb>
            <Ca>434.75</Ca>
            <Cb>-0.508</Cb>
    </PeriodData>
</Table>
```


B.4. INITIAL RUNOFF.DPR


```
{
    "hideOriginal" : true,
    "presets" : {
        "Initial Runoff" : {
            "Number of Divisions": 20.00,
            "Override Roof RC": {"fastMode":true, "value":false},
            "New Roof RC": 0.00,
            "Floor Type": {"value": "Residential", "values":
["Residential","Business","Industrial","Lawns","Parks/Cemeteries","Playgrou
nds","Walks","Streets","Forest","Meadow","Agricultural land"]},
            "Override Floor RC": {"fastMode":true, "value":false},
            "New Floor RC": 0.00,
            "Topography Type": {"value": "Residential", "values":
["Residential","Business","Industrial","Lawns","Parks/Cemeteries","Playgrou
nds","Walks","Streets","Forest","Meadow","Agricultural land"]},
            "Override Topography RC": {"fastMode":true, "value":false},
            "New Topography RC": 0.00,
            "Override Intensity": {"fastMode":true, "value":false},
            "Return Period (years)": {"value": "10", "values":
["2","5","10","20","50","100"]},
            "Pluviometric Zone": {"value": "A", "values": ["A","B","C"]},
            "Storm Duration (min.)": 0.00
        }
```

```
    }
}
```

B.5. LIDBMP.DPR


```
{
    "hideOriginal" : true,
    "presets" : {
        "LIDBMP" : {
            "Roof Area": 0.00,
            "Floor Area": 0.00,
            "Topography Area": 0.00,
            "Roof RC": 0.00,
            "Floor RC": 0.00,
            "Topography RC": 0.00,
            "Intensity (m/h)": 0.00,
            "Duration (min)": 0.00,
            "Initial Runoff (L)": 0.00,
            "Use LEED settings?": {"fastMode":true, "value":true},
            "LEED Credit": {"value": "LEED ND", "values": ["LEED ND","LEED
BD+C","LEED BD+C: Homes/Multifamily Midrise","LEED ID+C","LEED O+M"]},
            "or desired final runoff (L)?": 0.00,
            "LIDBMP 1": {"value": "", "values": ["Green Roof","Permeable
Pavement","Rain Gardens/Swales","Rain Barrels/Cisterns"]},
            "LIDBMP 2": {"value": "", "values": ["Green Roof","Permeable
Pavement","Rain Gardens/Swales","Rain Barrels/Cisterns"]},
            "LIDBMP 3": {"value": "", "values": ["Green Roof","Permeable
Pavement","Rain Gardens/Swales","Rain Barrels/Cisterns"]},
            "LIDBMP 4": {"value": "", "values": ["Green Roof","Permeable
Pavement","Rain Gardens/Swales","Rain Barrels/Cisterns"]},
            "Maximum number of barrels": 0.00,
            "Priority BMPs order?": {"fastMode":true, "value":false},
            "Minimum Area?": {"fastMode":true, "value":false},
            "Minimum Cost?": {"fastMode":true, "value":false}
        }
    }
}
```